Final Report

Impulse Noise Bearing and Amplitude Measurement and Analysis System (BAMAS)

SERDP Project SI-1427

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Mr. Jeffrey Allanach
Mr. Justin Borodinksy
Mr. Bruce Abraham
Applied Physical Sciences Corporation

Strategic Environmental Research and Development Program

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14. ABSTRACT

The BAMAS project addresses SERDP CPSON 05-04 for improving the measurement, analysis, archiving and reporting of impulsive acoustic noise emanating from within a military installation. Impulsive noise events that cause public alarm are loud, high signal-to-noise ratio, short-duration acoustic pulses from explosions, impacts, large caliber artillery fire, and sometimes sonic booms. Impulsive noise monitoring systems play a critical role in the relationship between test and training managers, environmental safety/compliance officers and the general public residing adjacent to military installations. Noise monitoring systems are needed for quantifying the magnitude and time of impulsive noise events, to ensure compliance and to provide an archival record of noise emanating from the installation. There are several commercial systems currently available however they can report an overwhelming number of false events as a result of windborne noise and distant non-military acoustic events. This can bias noise statistics to the point where meaningful assessment of the acoustic sound levels from a site is not possible. APS, in collab

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List of Acronyms

A/D	Analog to Digital Converter
APS	Applied Physical Sciences Corp.
BAMAS	Bearing and Amplitude Measurement and Analysis System
CSV	Comma Separate Values
DOA	Direction of Arrival
FAR	False Alarm Rate
NI-DAQ	National Instruments Data Acquisition
NTP	Network Time Protocol
KML	Keyhole Markup Language
pdf	Probability Density Function
RMSE	Root Mean Square Error
SERDP	Strategic Environmental Research and Development Program
SNR	Signal to Noise Ratio
SPL	Sound Pressure Level
UTC	Coordinated Universal Time
XML	Extensible Markup Language

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Abstract

The BAMAS project addresses SERDP CPSON 05-04 for improving the measurement, analysis, archiving and reporting of impulsive acoustic noise emanating from within a military installation. Impulsive noise events that cause public alarm are loud, high signal-to-noise ratio, short-duration acoustic pulses from explosions, impacts, large caliber artillery fire, and sometimes sonic booms. Impulsive noise monitoring systems play a critical role in the relationship between test and training managers, environmental safety/compliance officers and the general public residing adjacent to military installations. Noise monitoring systems are needed for quantifying the magnitude and time of impulsive noise events, to ensure compliance and to provide an archival record of noise emanating from the installation. There are several commercial systems currently available however they report excessive false positives as a result of windborne noise and distant non-military acoustic events. This can bias noise statistics to the point where meaningful assessment of the acoustic sound levels from a site is not possible. APS, in collaboration with the University of Pittsburgh, have developed an improved noise monitoring system, called BAMAS (Bearing and Amplitude Measurement and Analysis System), for mitigating windborne and other sources of non-military noise. This system includes a collection of remote sensors capable of detection, localization, and classification. Each sensor uses an acoustic array and real-time signal processing codes to estimate the noise source location. Mitigation of windborne events is accomplished using cross-channel correlation analysis, beamforming, and classification. The classifier developed under separate SERDP programs, SI-1436 and SI-1585, was developed by the University of Pittsburgh and integrated by APS into the BAMAS software. A prototype of this system is installed at an active military base where it has been reporting and archiving impulse noise since October of 2009. In just 2 months, the BAMAS system has archived over 3000 events of which none were incorrectly classified as blast noise during periods of significant wind. Data presented in this report was extracted from unprocessed (raw microphone data) and processed (algorithm output) data recorded by the BAMAS sensors during field testing. The BAMAS algorithm was found to reject 99.5% of the non-blast noise (specifically wind) recorded while retaining 97.7% of all blast noise with sufficient signal-to-noise ratio (SNR).

Objectives

The goal of the BAMAS project is to develop a noise monitoring system for military impulse noise that provides improved noise measurement capabilities and is more reliable than existing systems. Specific technical objectives achieved during the two phases of work include:

1. Provide improved basic impulse noise measurement approach that rejects essentially all (e.g. > 99%) nonacoustic, wind-induced false-positive noise events.
2. Provide improved situational awareness by automatically measuring direction of arrival (DOA) or bearing for each noise event. Provide automated source range localization and effective source strength (amplitude at source) when multiple installation sites are used.
3. Improved impulse noise reporting interface. Integrate new bearing and source amplitude information into PC-based control and display interface using map-based approach. Source information will be used to estimate sound levels in sensitive areas, such as residential communities near base borders. Users will be automatically alerted if a specified threshold is exceeded. This threshold can be based on the event amplitude, number of events in a given time period, or both.

Research and development of the BAMAS system was accomplished under a two phase effort. Phase I was a proof-of-concept effort focused on preliminary measurements of impulse noise and algorithm design. The major objective in Phase II was to develop, test, and demonstrate two prototype BAMAS noise monitors. Specific objectives during each task are outlined below:

Phase I: Proof-of-Concept Data Collection and Algorithm Design

i. Microphone and Array Design: Requirements for individual microphones and microphone array were developed. The array design criteria included, among others, angular resolution, frequency range of operation, and dynamic range. Design issues included minimizing the number of sensors, the transducer type (e.g. condenser vs. piezoelectric), cost, power, and size.
ii. Algorithm Development: Here we developed algorithms for impulse noise bearing and range determination and noise feature extraction/classification. The algorithms were developed and tested in MATLAB.
iii. Prototype System Design, Assembly, and Bench-Testing: A reconfigurable multi-microphone array was assembled and bench-tested. Signal outputs were recorded and analyzed to prepare for field testing. The algorithms were functionally checked and debugged with recorded data sets.
iv. Preliminary Field Testing: During this task we collected data needed to complete the array design. Several different array configurations were tested and the performance of each candidate was evaluated in terms of detection and bearing accuracy as well as SNR improvement. Baseline measurements with a condenser microphone, similar to what is used in existing systems, was made simultaneously to provide a quantitative comparison.

Go/No-Go Milestone: False Alarm Rate Reduction

The Go/No-Go decision for the BAMAS system was based upon whether or not the algorithms developed in Phase I could sufficiently reject events generated by windborne noise. APS developed a computer simulation (based on real wind data) to evaluate the false alarm rate (FAR) as a function of detector threshold. Conclusions drawn from this experiment show that a small array of four (4) microphones can improve the FAR of existing systems (i.e. single microphone with simple detection processing) by a factor of 1000. Moreover, it was discovered that each additional microphone will improve the FAR by a factor of 10. The upper bound on FAR as a function of channel count was not investigated since an array of more than 10 microphones would be exceedingly complex and expensive. This result led to a positive Go/No-Go decision.

Phase II: System Prototype Development and Demonstration

i. System Development: Design, fabricate, and test 2 BAMAS noise monitors.
ii. Code Development, Testing, and Integration: Algorithms developed in Phase I by APS were converted to C and ported to an embedded Linux PC/104 computer which each BAMAS sensor uses to process data in real-time.
iii. Classifier Integration and Testing: A classification algorithm developed by the University of Pittsburgh was integrated into the BAMAS real-time software. APS and University of Pittsburgh participated in a preliminary bench test that real recorded waveforms of blast noise to validate the functionality of the software and algorithms.
iv. Field Testing: 2 BAMAS sensors and 1 base station were built, tested, and installed near existing noise monitors at an active military base. The system has been operational since October of 2009 and has detected over 3000 verified military acoustic impulse noise events. Data collected by each sensor is stored locally and was downloaded for performance analysis. This effort will be discussed further in the Results section.

Background

Current military noise monitoring systems do not accurately detect and classify military noises, are plagued by wind noise, report an unacceptable amount of false positives, and miss military noise events that occur below a peak level of 115 dB re. 20 µPa. In an attempt to reduce the number of false positives caused by wind noise, researchers have investigated various methods including the use of:

(1) Multiple pressure sensors and cross-channel analysis [3], [4], [5].
(2) Combination of geophone and pressure sensor [3], [6], [10].
(3) Statistical modeling and classification algorithms [7], [8].

Most have been demonstrated in laboratory experiments however few have had success in operational environments. The first technique, to use multiple microphones, was first demonstrated with computer simulations (Monte Carlo runs) and provided 97.5% detection rate and a 2.5% FAR. Some limited field testing of this system was performed in 1999 with good results, but ultimately this technique was not widely adopted by manufacturers and to-date has only been deployed at one location. This system is currently not operable.

The combination of geophone and pressure sensor was a novel idea for rejecting wind-based false positives and was originally developed as a sonic boom detection system [10]. This method was supposed to reject wind noise by correlating the outputs of the microphone and geophone, however severe differences between the in-air and in-ground wave fronts, particularly their propagation delay, made it difficult to correlate these measurements. Additionally, ultra-sensitive geophones are designed to detect large amplitude seismic or in-air events like sonic booms (peak overpressures from 1-10 lb/ft^2) but may not be sensitive enough for lower amplitude signals like blast noise that can cause public alarm (100 dB re. 20µPa or 2.9 x 10^{-4} lb/ft^2).

A third method, to develop a classification algorithm [8],[9] is being addressed by another SERDP program (SI-1585) headed by the University of Pittsburgh. Their neural-net based classifier uses salient features of the signals to discriminate between wind and blast noise. This algorithm was trained using a large dataset of recorded waveforms collected from many military installations. Preliminary results indicate that its FAR is quite low (99.6% accuracy).

Our approach to rejecting wind noise is similar to the first method, but uses a four-element microphone array (as opposed to just 2) and rigorous array processing. In addition to measuring the cross-correlations between sensors as in (1), our algorithm measures the intra-channel time delays and compares these to an *a priori* model of expected acoustic time delays from all DOAs. In essence, our approach measures the wave front propagation speed and rejects signals that travel slower or faster than the speed of sound. Maximum wind speeds are many times slower than the speed of sound so it is relatively easy to reject false wind triggers. One of the added benefits of our methodology includes the ability to estimate DOA (i.e. bearing and elevation) which enables Noise Managers to determine where blast events originate from.

In the following report we summarize the design, performance, and testing of BAMAS noise monitoring system and its integration with the University of Pittsburgh classification algorithm.

Materials and Methods

System Design

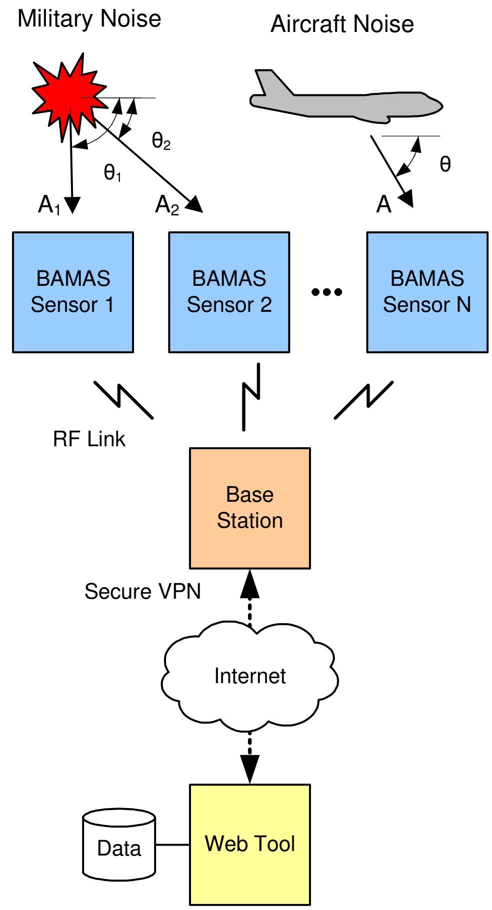


Figure 1: BAMAS System Design

The BAMAS system is a collection of remote sensors designed for detection, localization, and classification of environmental noise sources from military and aircraft noise. Military noise is characterized by loud, low frequency, short-duration acoustic pulses from explosions, impacts, and large caliber artillery fire. BAMAS sensors automatically detect and report these events using a calibrated acoustic array capable of resolving the direction of an incoming pressure wave. This array also provides the ability to mitigate false positive events created by windborne noise. Other noise monitoring systems lack this capability and therefore archive many false events during inclement weather – skewing detection statistics and post analysis. Additionally, the BAMAS real-time processor employs special detection and classification algorithms developed by APS and researchers at the University of Pittsburgh to provide a statistical measure of the likelihood of each detected event to further rule out unwanted false positives.

Each BAMAS sensor includes a 4 channel microphone array, solar panel, weather station, RF antenna, electronics panel, cabling, and mounting hardware. The system is intended for long term and permanent surveillance applications in remote locations with or without AC power. BAMAS sensors employ a low power PC/104 based processor and data acquisition modules running embedded Linux and real-time array processing code. Detected events are recorded locally and information regarding its bearing and amplitude are telemetered to a base station computer via a wireless Ethernet radio (either 900MHz or cellular). This data is fused at the base station with information from other BAMAS sensors and is sent to a secure MySQL database and accessible via our web-based tool. The online tool includes a database of events and a Google Earth map for visualizing their location. If a blast event is detected on more than one noise monitor, BAMAS can triangulate the location of offending noise source and will put a waypoint at that location on the Google Earth map. Peak level, time, location, classified output, DOA, filename and other information is easily viewed by clicking on individual waypoints.

The BAMAS software has been designed to minimize operator labor. Automated emails notify the user when the batteries get low or if a sensor goes offline. This functionality can be extended to situations when a certain number of events of exceedingly high amplitude are detected. This is not yet a feature of the BAMAS software but is planned for future development. Moreover, downloading event time series data is facilitated over the Ethernet connection and can be scheduled to download automatically during periods of little activity. Data presented on the secure BAMAS website is easily converted and viewed in other spreadsheet and analysis software programs. Currently, data may be converted to CSV, XML, or KML files. Most internet browsers may be configured to automatically load and display this data.

BAMAS sensors run real-time signal processing codes to estimate the noise source location and to reduce the possibility of false events. To reduce false positives as a result of windborne noise, the software measures the propagation speed of each pressure signal and rejects all that do not travel at the speed of sound – hence all non-acoustic events are discarded. Other noise monitoring systems use a single microphone and are therefore highly susceptible to reporting false detections.

Wind Rejection Concept and Algorithm

Each BAMAS sensor uses a microphone array (shown in Figure 2) which helps reject non-acoustic events using conventional frequency or time-domain beamforming (the software uses the later approach). True acoustic impulse events are discerned from wind noise by rejecting signals that do not propagate at, or near, the speed of sound. To further explain this approach, consider an acoustic wave propagating across an array of microphones as shown in Figure 2. The maximum time that an acoustic wave can take to travel from one sensor to another in this case is $\tau = s/c$ where c is the local speed of sound in air and s is the distance between them. If a wind gust induces an impulsive pressure event on a microphone, it is very unlikely to produce another impulse on adjacent microphone within the time τ.

Figure 2: BAMAS microphone array installed on radio tower

Even if similar pulses occur on different microphones, they will travel or convect at the mean wind speed. For example, a 40 knot gust traveling across a 4-ft diameter array will take 59 ms to cross whereas an acoustic wave will only take 3.6 ms. This significant difference in delay is used to reject essentially all non-acoustic noise. In the rare instance of a large down- or up-draft, a non-acoustic wind impulse may arrive at the sensors at very close times. The correlation [4],[8] between sensors can then be used as a secondary metric to reject non-acoustic noise. The normalized cross-correlation for two zero-mean, stationary signals (e.g. microphone pressures) over a finite time period can be estimated as,

$$R(\tau)=\frac{\frac{1}{T}\int_{t_1}^{t_1+T} p_1(t)\,p_2(t+\tau)}{p_{1,rms}\,p_{2,rms}}$$

Where "rms" denotes the root-mean-square for each pressure over the specified time period. High SNR acoustic signals will generate correlation functions with maxima near unity because there will be little attenuation of the wave across the relatively small microphone array. The turbulent fluctuations will generate much lower correlation functions (e.g. < 0.4) because of the nature of the turbulent flow over the microphones. Thus the cross-correlation function can be used to reject wind noise by examining both the time delays and maximum correlations between microphone signals. The cross-correlation function can also be used in time-domain beamforming for bearing estimation. During our Phase II work we discovered that the magnitude of the cross-correlation is not reliable for lower SNR targets, thus the current software version compares the time delays between each microphone with a look-up table of delays for every possible DOA. The error between the measured and estimated time delays is defined as,

$$\varepsilon^2(\theta,\phi)=\sum_i\left|\tau_i-\hat{\tau}_i(\theta,\phi)\right|^2$$

where *tau-hat* are the set of look-up table values for all incident angles theta and phi and *tau* are the set of measured time delays. If this error is sufficiently high, the incident signal is not likely to be a real acoustic impulse noise. The RMS error surface as a function of θ and φ for a measured blast is shown in Figure 3.

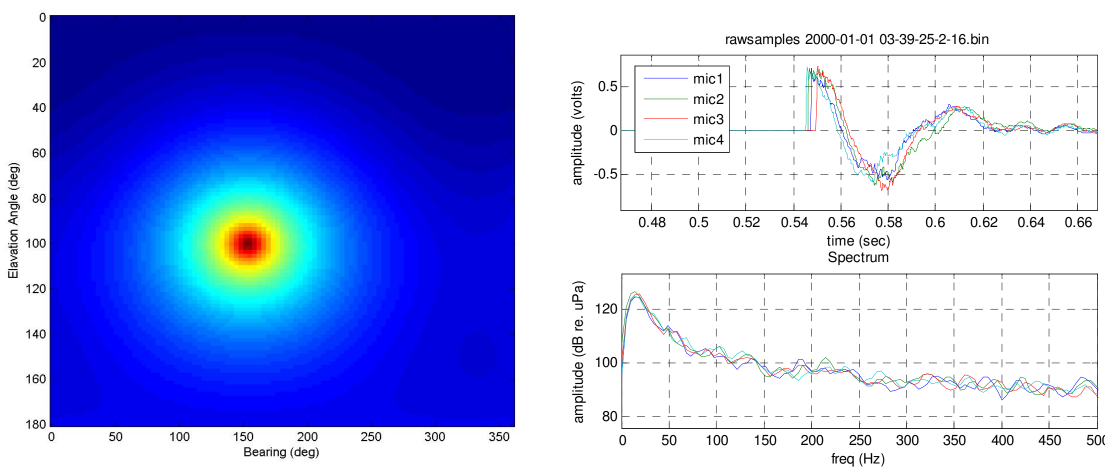


Figure 3: Error surface (left) for acoustic impulse (right) as measured by the BAMAS array and signal processing code. The blast signal is estimated to have been incident at 150 degrees bearing and 100 degrees elevation.

An algorithm implementing this methodology was developed in Matlab during Phase I and then converted to C during Phase II. A block diagram of this algorithm is shown in Figure 4. Noise levels that cause public alarm occur at a peak level greater than 100 dB ref 20 μPa, thus our threshold may be set to this or something lower. Our current software is set to analyze 1 second of data with 10% overlap in the event that the signal of interest is partitioned between two consecutive windows. Wind is spatially uncorrelated, so the algorithm checks to make sure that all channels exceed this threshold, otherwise, the event is rejected. If a particular event is truly acoustic, then each of the 4 channels will exhibit a similar response plus or minus a small time delay. Wind noise may not trigger all N channels unless the wind is significantly strong and spatially correlated across the entire width and height of the microphone array. Not surprisingly, this helps reject other false positive events. This detection criteria works well (i.e. reject more wind events) when the array elements are spaced far apart. For our purposes, the array design consists of 4 microphones spaced uniformly on a 6 ft diameter circle (each 120 degrees apart) with one, vertically offset 3ft from the center. We have considered adding another microphone channel to the system, but instead of including it in the array, spacing it a good 10-20 meters from the array so as to gain spatial diversity. The current system design includes a fifth microphone, a type 1.5 precision microphone (see Appendix for data sheet), used specifically for obtaining a best estimate of peak SPL and for classification.

The third and fourth components in Figure 4, labeled "Cross Correlator" and "Acoustic Likelihood Test", make up the beginning of the time domain cross-correlation based beamformer discussed earlier. In these steps we measure the channel time delays and compare them to a table of pre-computed time delays attributable to an acoustic wave traveling at the speed of sound from all possible DOAs. After we have computed the RMSE between the actual time delays and the expected time delays, we then search for its minimum value, the maximum likelihood estimate, and compare this value with a predefined threshold. For events that are truly acoustic and have sufficient bandwidth, the RMSE will be small. Events that exceed this threshold are rejected. A derivation of optimum threshold is outlined in Appendix II.

The final steps in this process, labeled "Beamformer" and "dB threshold", is meant to culminate all of our knowledge of the suspected impulsive event and take advantage of array gain to improve SNR. Here we perform a traditional delay-and-sum time domain beamformer. If real blast noise, the beamformer output will have the same magnitude as the channel inputs and will exceed the original threshold. Any event that surpasses the final threshold will be logged and made available for further processing.

The performance of this algorithm given simulated inputs was determined in Phase I (Figure 5 and Figure 6). The take away from this study indicated that the FAR of a microphone array decreases with increasing number of microphones that are sufficiently spaced. Later we will show that performance given real data, obtained during our Phase II field testing, yields similar results. Microphones are "sufficiently spaced" at distances where the spatial correlation of wind is low (i.e. < 0.2). The separation distance of the BAMAS array was designed to allow for accurate direction finding. The frequency of military blast noise can be as low as 10 Hz, thus wavelengths of up to 113ft are possible. As a rule of thumb, accurate DOA estimation is possible so long as at least 10° of phase (wavelength) accumulates as the wave front propagates across the microphone array. The wavelength at 10 Hz is 113ft which implies that approximately 3ft (10°) of microphone separation is necessary for an accurate DOA estimat.

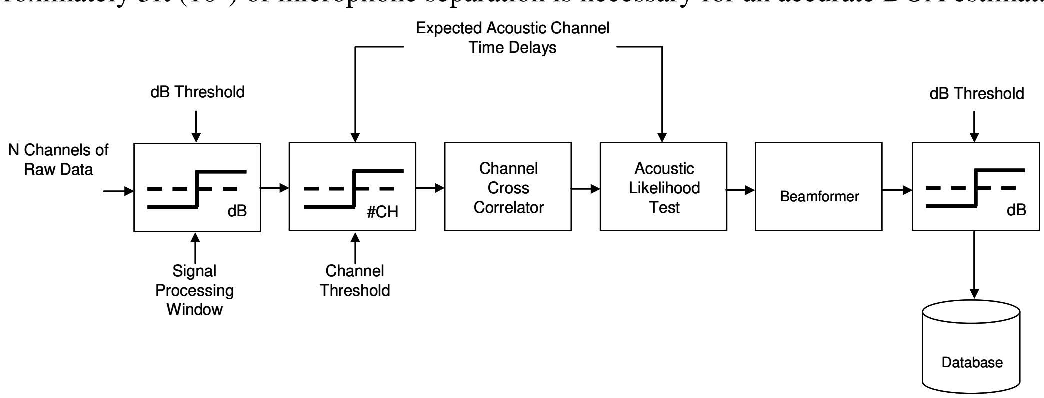


Figure 4: Time domain cross correlation detector for military blast noise

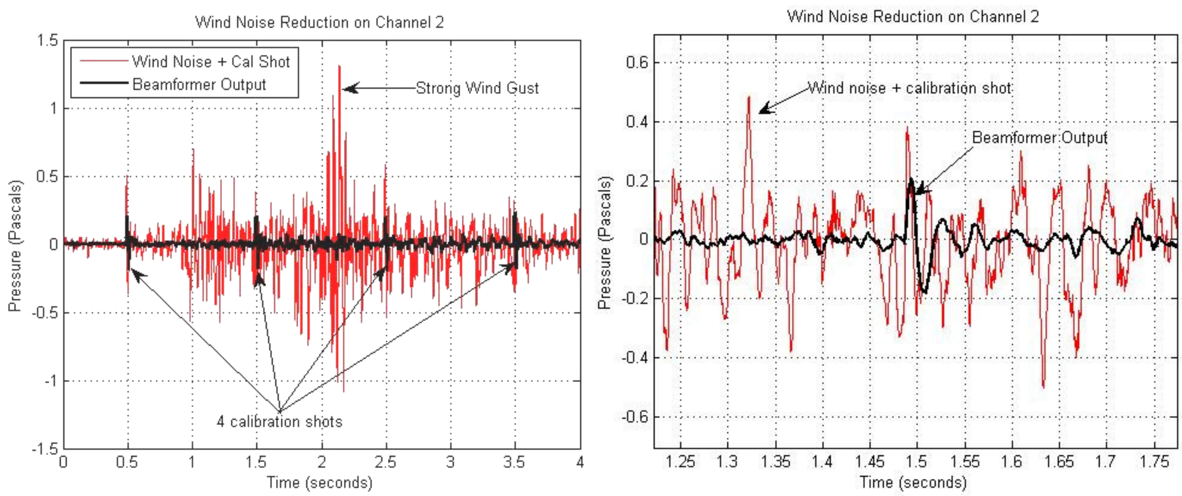


Figure 5: Simulated time series of wind and blast before (red) and after (black) beamforming. Beamforming performs spatial filtering by way of averaging all of the channels in the array. Since wind is generally incoherent between sensors (at distance), the summation of the channels coherently destructs the affect of windborne noise and pronounces the true acoustic signal.

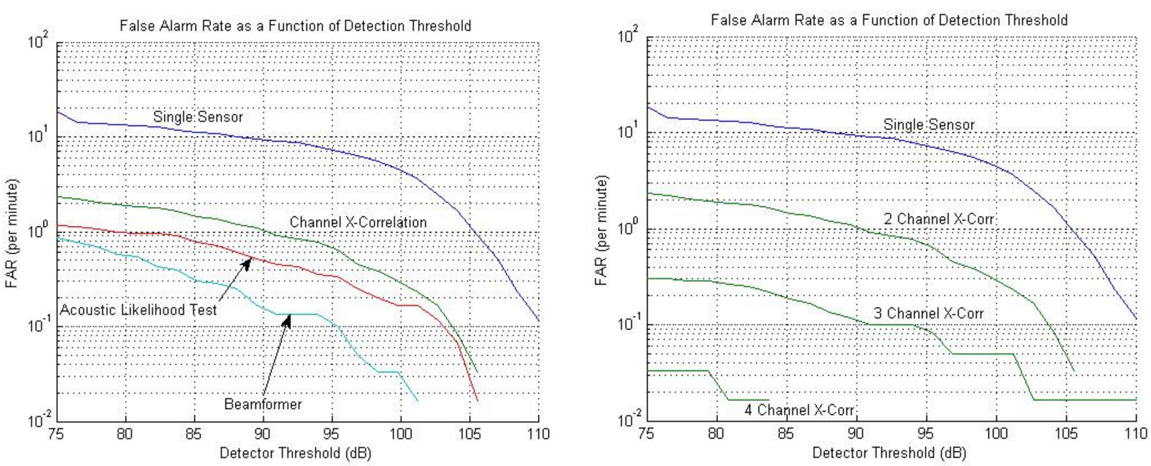


Figure 6: Simulated performance of detection algorithm in comparison with "Single Sensor". The false alarm rate (FAR) decreases with each additional processing technique (left) and with increasing number of sensors (right). With this algorithm, a small array of 4 sensors will report 1000 times less false alarms than a similar single sensor system.

BAMAS System Hardware Design

A detailed block-diagram of the BAMAS hardware architecture is shown in Figure 7. Each BAMAS sensor (2 are shown) communicates to a base station computer (Windows or Linux PC) using a wireless Ethernet bridge. This wireless connection can be facilitated using a 900MHz FreeWave radio or using a Digi Cellular modem. During our Phase II field testing we chose to use the 900MHz link since the military base where our testing took place already had radio towers at each of the noise monitoring locations. We included the option for cellular communications because not all military bases have radio towers and will therefore require another form of communications.

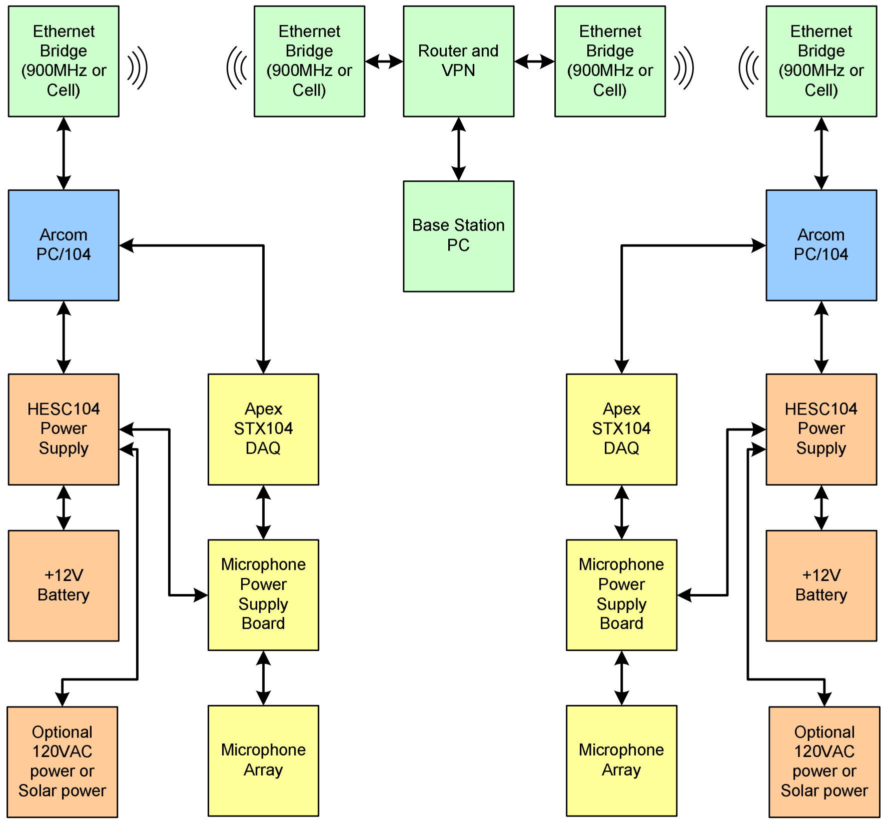


Figure 7: Block diagram of two BAMAS noise monitors and base station.

Each BAMAS sensor has a PC/104 computer and data acquisition system. The BAMAS real-time code runs on an Arcom Viper PC/104 with embedded Linux. This employs a very low power (2W) Intel processor (the PXA254) suitable for battery powered applications. The data acquisition module is an Apex Embedded STX104 capable of 16 channels at 200kHz. Power for all of the boards is distributed by a Tri-M HESC104 power supply module. The microphone array inputs are connected to a custom designed electronic board that provides gain, filtering, and power to the array. Moreover, a microcontroller on this board can power ON/OFF the computer to conserve power or to restart the software. This power ON/OFF feature is remotely controlled from the base station computer using the wireless radios. A picture of the BAMAS computer is shown in Figure 8. Connections to this box include:

- +12 VDC Power Input
- Wired Ethernet Port
- ON/OFF switch
- Comms Switch (switches between wired and wireless Ethernet)
- Anemometer Input
- ACO Microphone Input
- Microphone Array Input
- Wireless Ethernet RF Coax Output

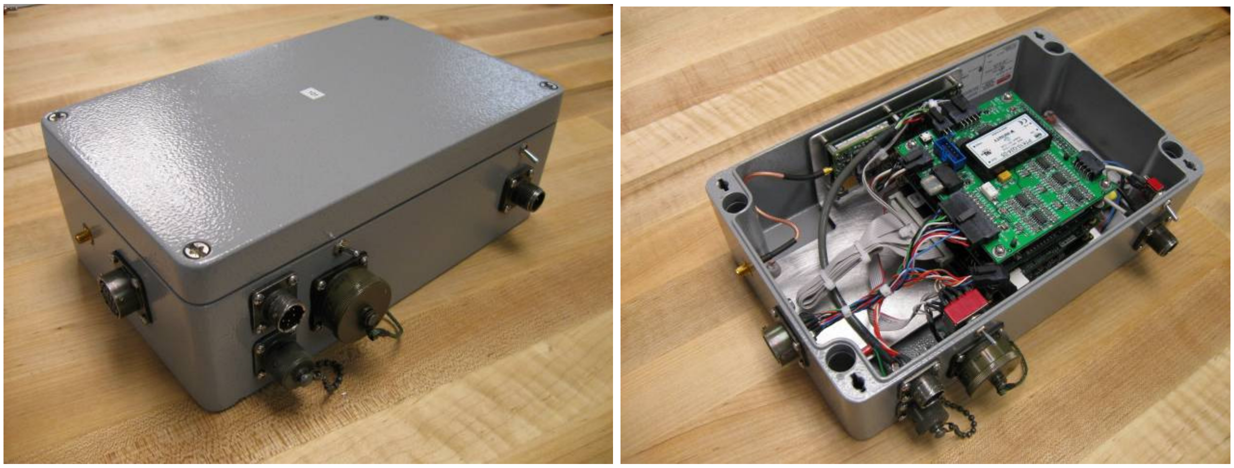


Figure 8: Linux PC/104 computer, Ethernet radio, and custom electronics box.

The BAMAS computer fits inside a weatherproof enclosure which also protects a 12V lead acid battery, a solar power battery charger, and a lightning arrestor. Cables into the weatherproof enclosure come from the BAMAS microphone array, an external anemometer, and a 50W solar panel (Figure 2).

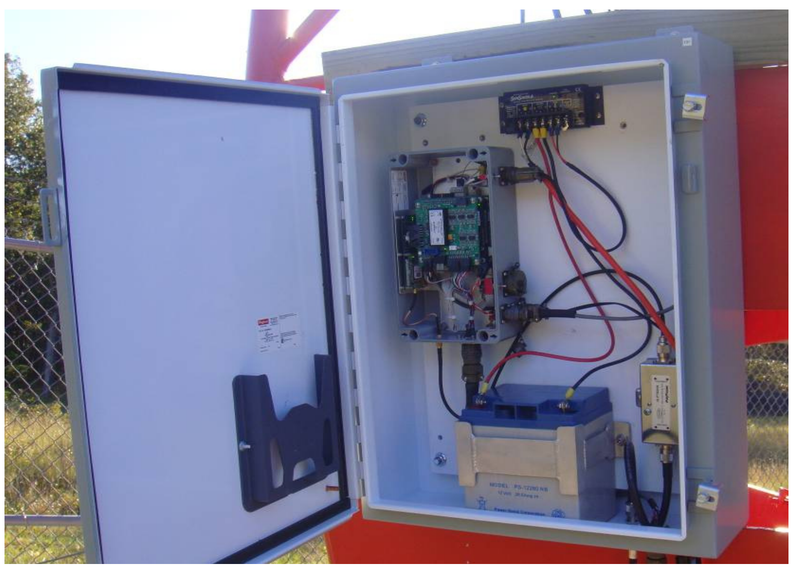
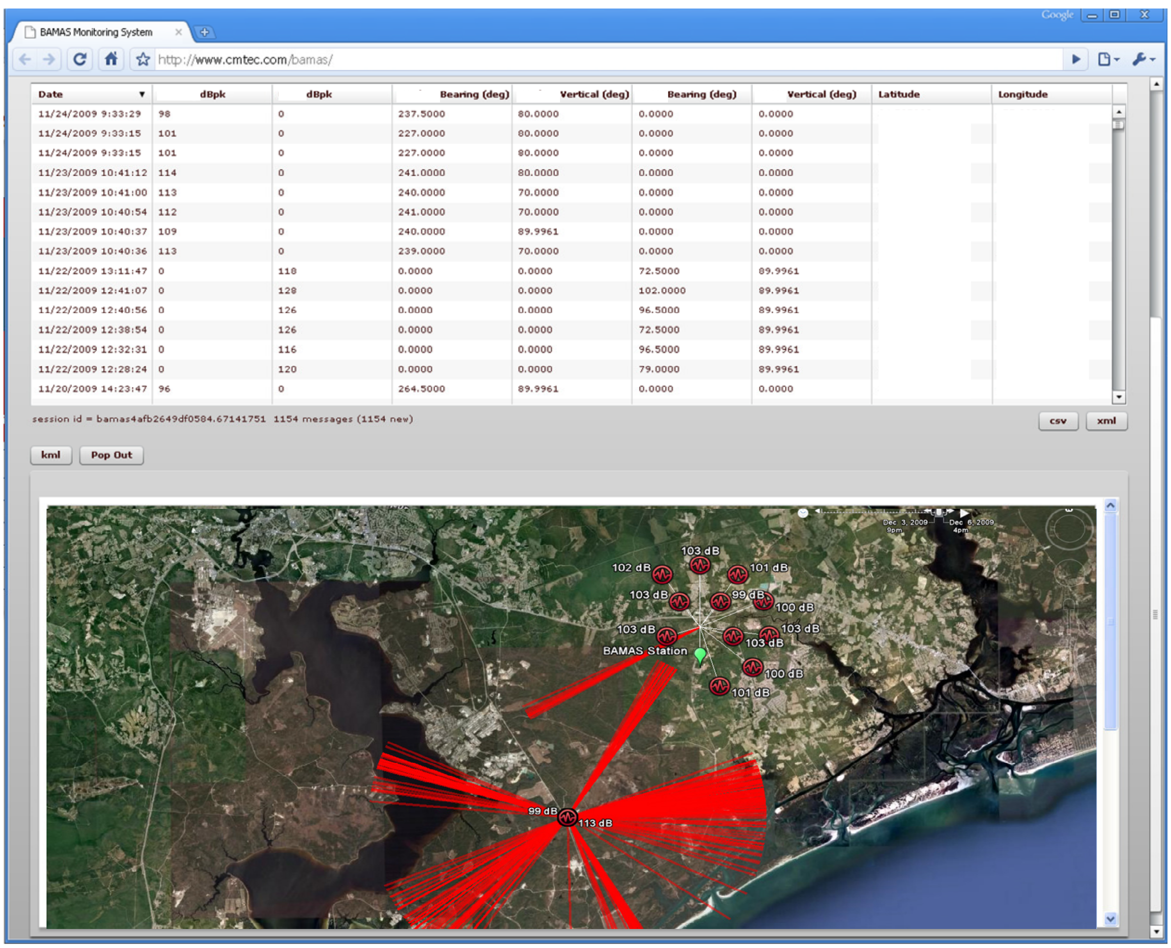


Figure 9: BAMAS weatherproof enclosure, battery, and solar charger

The BAMAS microphone array (Figure 2) consists of 4 Knowles BL-7242 0.5" microphones. These are low cost microphones used to help mitigate windborne noise and estimate blast noise DOA. In addition to these, the BAMAS system uses an ACO Pacific 7052LF/4052LF microphone/preamp pair that is specially designed for OEM noise monitoring. This microphone/preamp pair was chosen for its low-frequency response (-3dB down at 0.5Hz) which is critical for measuring military impulse noise. Specification sheets for each microphone are attached to the Appendix.

BAMAS Software Design

APS developed a website (Figure 10) for the BAMAS system which allows authenticated users to visualize a database of archived blast events. Double-clicking on an event in the table will automatically render the Google Earth map to display that particular event alone. Users can also display a range of events including "today", "this week", and "this month". The website also allows users to download this information to a comma separated values (CSV). CSV files can be directly imported into Microsoft Excel. The web interface also provides the option to download a KML file which can be imported into Google Earth. The data shown in Figure 10 is from our Phase II field testing. The red lines emanating from each of the 2 BAMAS noise monitors indicates the DOA of a particular blast noise. Where these red lines cross indicates the location of where the blast took place. The accuracy of the source localization is dependent on the SNR, the time bandwidth of the signal, and the number of BAMAS noise monitors that detected the event, their geometry (i.e. geometric dilution of precision), and the prevailing weather conditions. We learned during our Phase II field testing that the wind direction and speed can significantly alter the DOA of blast noise. Future improvements to the BAMAS software could fuse data from acoustic propagation models to provide better performance.



Date	dBpk	dBpk	Bearing (deg)	Vertical (deg)	Bearing (deg)	Vertical (deg)	Latitude	Longitude
11/24/2009 9:33:29	98	0	237.5000	80.0000	0.0000	0.0000		
11/24/2009 9:33:15	101	0	227.0000	80.0000	0.0000	0.0000		
11/24/2009 9:33:15	101	0	227.0000	80.0000	0.0000	0.0000		
11/23/2009 10:41:12	114	0	241.0000	80.0000	0.0000	0.0000		
11/23/2009 10:41:00	113	0	240.0000	70.0000	0.0000	0.0000		
11/23/2009 10:40:54	112	0	241.0000	70.0000	0.0000	0.0000		
11/23/2009 10:40:37	109	0	240.0000	89.9961	0.0000	0.0000		
11/23/2009 10:40:36	113	0	239.0000	70.0000	0.0000	0.0000		
11/22/2009 13:11:47	0	118	0.0000	0.0000	72.5000	89.9961		
11/22/2009 12:41:07	0	128	0.0000	0.0000	102.0000	89.9961		
11/22/2009 12:40:56	0	126	0.0000	0.0000	96.5000	89.9961		
11/22/2009 12:38:54	0	126	0.0000	0.0000	72.5000	89.9961		
11/22/2009 12:32:31	0	116	0.0000	0.0000	96.5000	89.9961		
11/22/2009 12:28:24	0	120	0.0000	0.0000	79.0000	89.9961		
11/20/2009 14:23:47	96	0	264.5000	89.9961	0.0000	0.0000		

Figure 10: The BAMAS website displays a table of archived blast noise and a satellite map for visualizing the direction and/or location of the blast source. The table displays the time, magnitude (dB peak), bearing, elevation, latitude, and longitude from each noise monitor. The data shown above is based on data collected

in the field by 2 BAMAS sensors. Users may click on individual waypoints to view specific information regarding that particular event.

The BAMAS base station user interface (Figure 11) is designed to monitor the health of each BAMAS sensor on the network. The columns represent individual BAMAS sensors and the rows represent the latest information received from each. Information for Node 2 indicates that it is online (the green check), its battery is 14.61V, the last communication with it was 01/06/2010 at 16:05 hours, the last recorded wind speed was 0.8 mph, the last recorded wind direction was 198.71 degrees, and the sensor temperature (inside the computer box) is 64.77 °F. At the time this screen shot was taken there was no previous detections logged therefore the magnitude of the last detection (in dB ref 20µPa) is blank. Buttons at the bottom of each column allow the user to reset the sensor in the event that it goes offline or to download raw data. Data download is an important feature because it allows the user to listen to the unprocessed microphone signals. Currently, the base station software can support up to 25 sensors.

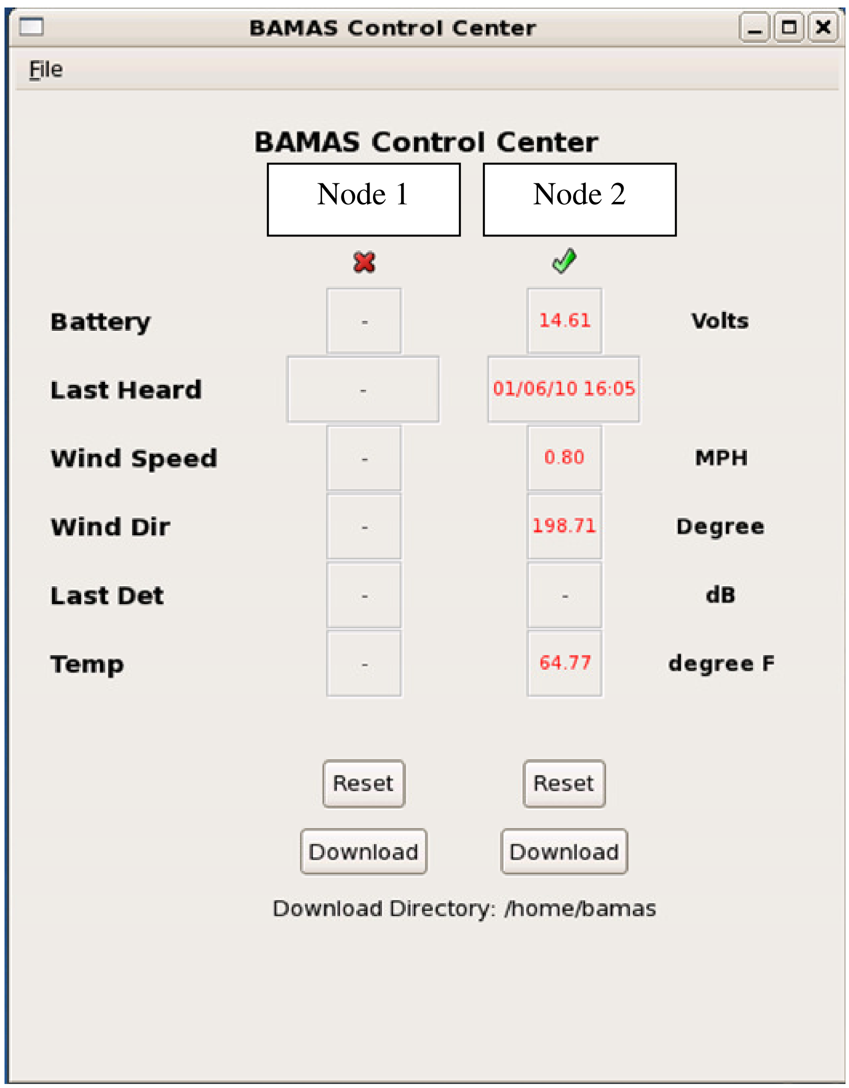


Figure 11: BAMAS Base Station Control GUI.

Results and Discussion

Demonstration of the BAMAS system, its software, and underlying concept were performed through a series of laboratory and field tests. Laboratory experiments during the early part of Phase II were used to validate the basic functionality of the software. Once it was determined that both BAMAS noise monitors were functioning properly, they were installed at an active military base. In order to collect sufficient detection statistics we left these noise monitors on location for over 2 months (end of October through end of December, 2009). Preliminary results indicate that the basic functionality of the system (i.e. detect, report, archive, notify) works as described earlier. In this section we will discuss our laboratory experiments and field testing.

Laboratory Experiments

Prior to field deployment, APS and the University of Pittsburgh performed a series of laboratory tests to ensure the functionality, calibration, and performance of the BAMAS system and its software components. The objectives of these tests were to:

1. Demonstrate:
    a. Wireless connectivity between BAMAS sensors and base station
    b. Data archiving and log file creation
    c. Time synchronization between sensors and base station
    d. Source localization using 2 BAMAS sensors
    e. Integration of BAMAS code and University of Pittsburgh classification algorithm
    f. Base station health monitoring and automated email generation
2. Determine if BAMAS algorithm properly detects and disseminates true acoustic signals from spurious false positive wind events
3. Determine that the University of Pittsburgh classification algorithm properly classifies true acoustic signals and spurious false positives
4. Measure and calibrate microphone arrays using sound level calibrator
5. Measure effective acoustic noise floor on each microphone channel
6. Measure DOA and source localization error using fixed point algorithm and simulated inputs
7. Measure algorithm calculation time to ensure software will maintain real-time operation

A block diagram of the test apparatus is shown in Figure 12. Two National Instruments data acquisition modules (NI-DAQs) were used to inject recorded acoustic impulse noise data directly into the A/D module inside the BAMAS computers (Figure 8). Each NI-DAQ streamed 4 independent channels of data to simulate the 4 channel microphone array. This allowed us to phase delay the impulse waveforms in order to simulate receiving the signal from different directions (in both elevation and bearing). Moreover, we could simulate the propagation delay between both BAMAS sensors. The computer controlling this signal generation was also used to run the BAMAS base station software. When detections were received, the base station software generates an email which is sent to our bamas@gmail.com account. Once the email is received, the BAMAS website downloads it, and then updates the database and user display. This entire process was verified during this bench testing.

With control of the signal phase and propagation delay we were able to simulate blasts from any latitude/longitude. Figure 13 illustrates the result from one test performed where we simulated a blast occurring every 2 seconds from a different latitude/longitude. The locations of each blast were defined by a semicircle surrounding BAMAS node #1. Node #2 can be seen at the perimeter of the semicircle. These tests validated that the beamforming and DOA estimation algorithms work properly. It should be noted that each of the waypoints in Figure 13 was localized using data from both sensors.

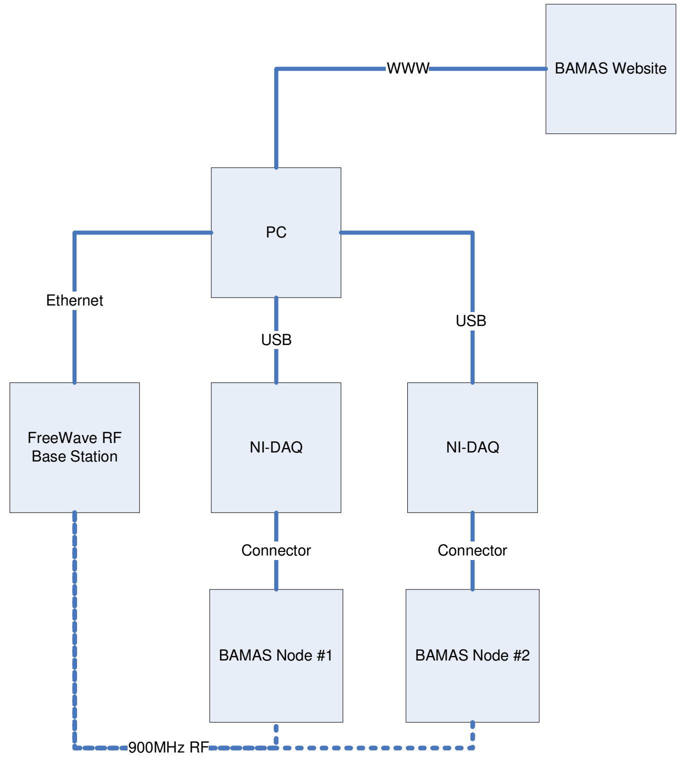


Figure 12: Block diagram of test setup during bench testing.

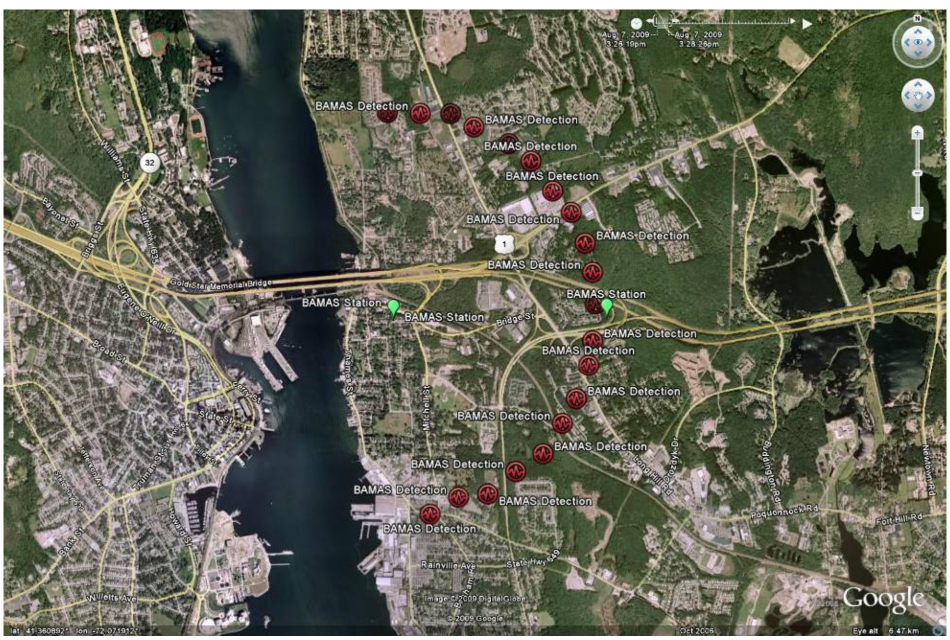
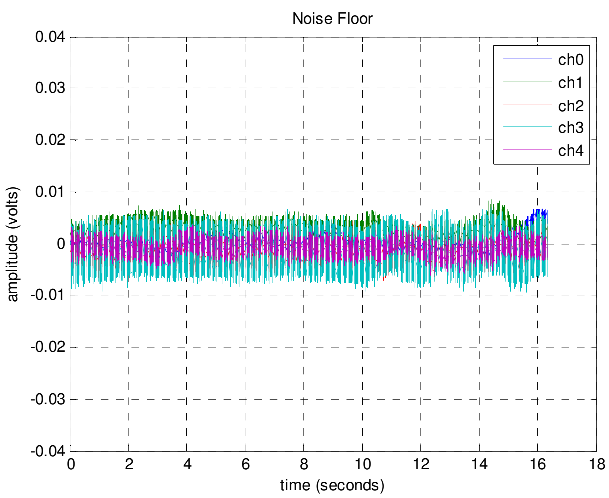


Figure 13: A result from BAMAS bench test. The green waypoints represent the simulated locations of the BAMAS sensors. The red waypoints represent a blast noise that was properly detected, classified, and triangulated. This test was repeated for different types of recorded blasts.

Other laboratory tests:

- verified that the bearing accuracy of the algorithm was less than **1 degree** for signals with good SNR
- proved that the algorithm data processing takes less than **500ms** (800ms was the limit)
- verified that the time synchronization between BAMAS sensors is **less than 1ms**
    - o Noise monitor time synchronization is critical for measuring propagation times. Most remotely deployed systems use time synchronization signals provided by GPS units, however, the BAMAS software uses the Network Time Protocol (NTP) for simplicity. NTP is a specially designed protocol for synchronizing the clocks of computer systems over packet-switched, variable-latency data networks. NTP can be accurate to within 200µs and provides Coordinated Universal Time (UTC) just like GPS devices.
- revealed that the effective ambient noise floor (Figure 14) is **75 dB ref 20µPa**
- validated the free-field voltage sensitivity of the microphones (to within 1dB of their specified levels at 1kHz using an SPL meter).



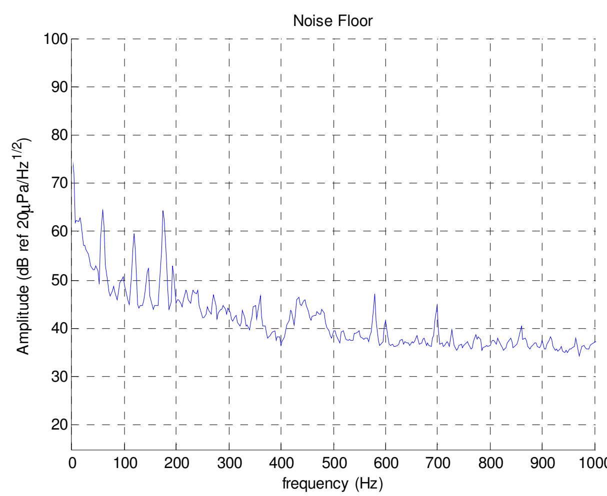


Figure 14: Time series (left) and spectrum (right) of the effective ambient noise floor of the BAMAS system. The left shows all five channels and is expressed in volts. An RMS level of 3.5mV translates to 75 dB ref 20µPa acoustic. All of the tones on the right were caused by our laboratory environment (i.e. 60 Hz and other harmonics can be seen) and are not seen in measured field data.

Figure 15 shows a preliminary acoustic test of the BAMAS sensors. This was performed near the APS parking lot in Groton, CT using a high power subwoofer and recorded blast waveforms. This test helped verify system functionality using real data recorded by the microphone array.

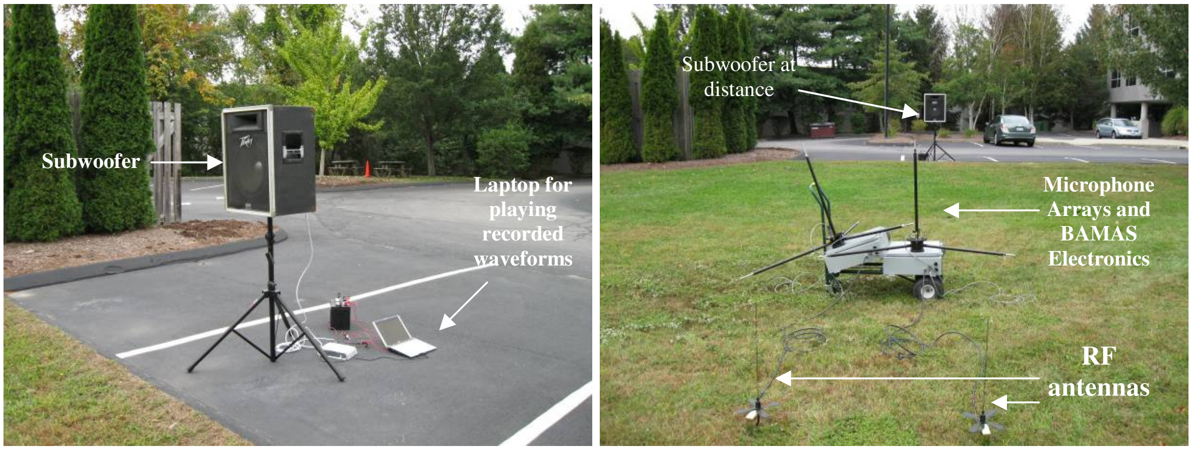


Figure 15: Preliminary acoustic test of both BAMAS sensors.

Field Testing

Two BAMAS noise monitors, that we will refer to as node #1 and node #2, were installed at a military base and data from each was collected over a period of 2 months (October – December, 2009). Node #1 is attached to a tall radio tower nearby a residential community. An existing noise monitoring system is also located there, however it is not functioning properly and therefore a comparison could not be made. Node #2 is located on top of an observation tower (Figure 17) which made for excellent radio communications with the base station. We discovered that establishing reliable radio communications is challenging and expensive. For the week that we were on location, this consumed about 3 days. APS has recently developed a new BAMAS sensor that uses a cellular modem instead of a traditional UHF or VHF radio. This will alleviate the cost and complexity of an RF survey.

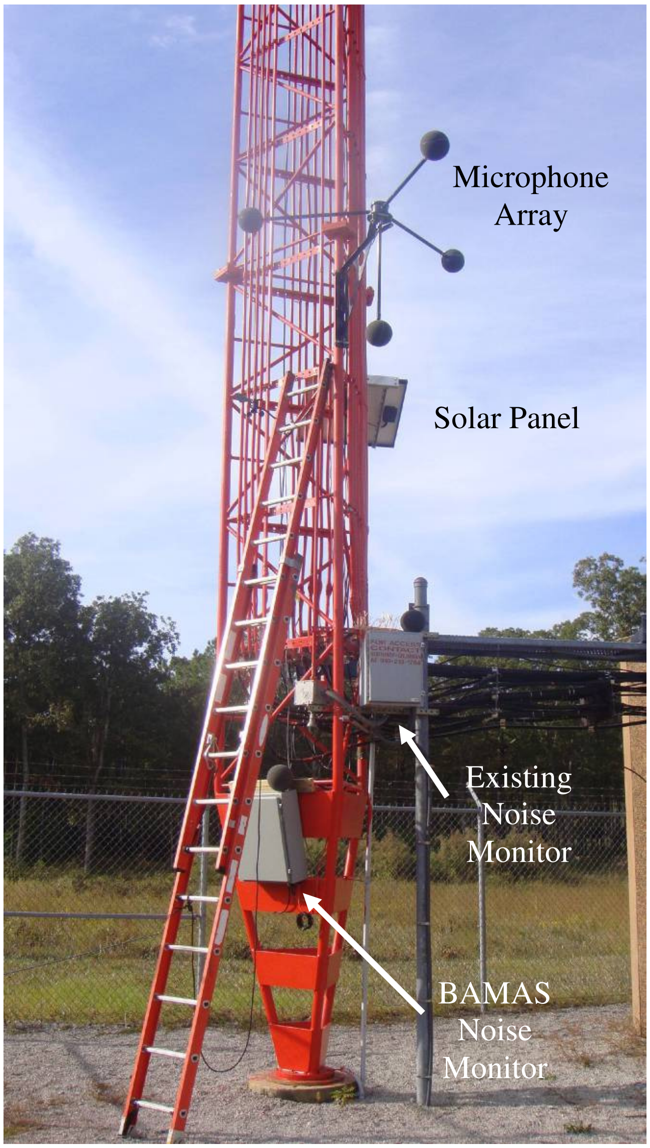


Figure 16: Node #1 installation.

Node #1 (Figure 16) is located 5 miles north-east of the primary blast zone. Node #2 (Figure 17) is located 1 mile south-west. Since node #2 is so much closer to the blast zone than node #1, most of the blast noise was measured at node #2 and only a few blasts were detected at node #1.

During our week of onsite testing we learned that there were a number of local acoustic and electrical disturbances which inadvertently caused the BAMAS monitors to falsely report. All of the radio towers at this military installation hosted 2 or 3 different high power radar and RF systems. When active, these high voltage systems generated significant electrical noise which corrupted the microphone signals. This noise was transient in nature, thus we had to reprogram the nodes to reject them – this was fortunately easy to do and it no longer has an adverse affect on our system other than reducing SNR. In addition to electrical disturbances, we observed that each of the two locations we were monitoring had high ambient (acoustic) noise levels. This appeared to be caused by the air conditioning units that cooled the electronics which in turn powered the radar antennas on the tower. This non-blast noise is rejected by the classifier so it had no adverse affect other than decreasing the signal-to-noise ratio of received acoustic impulse noise.

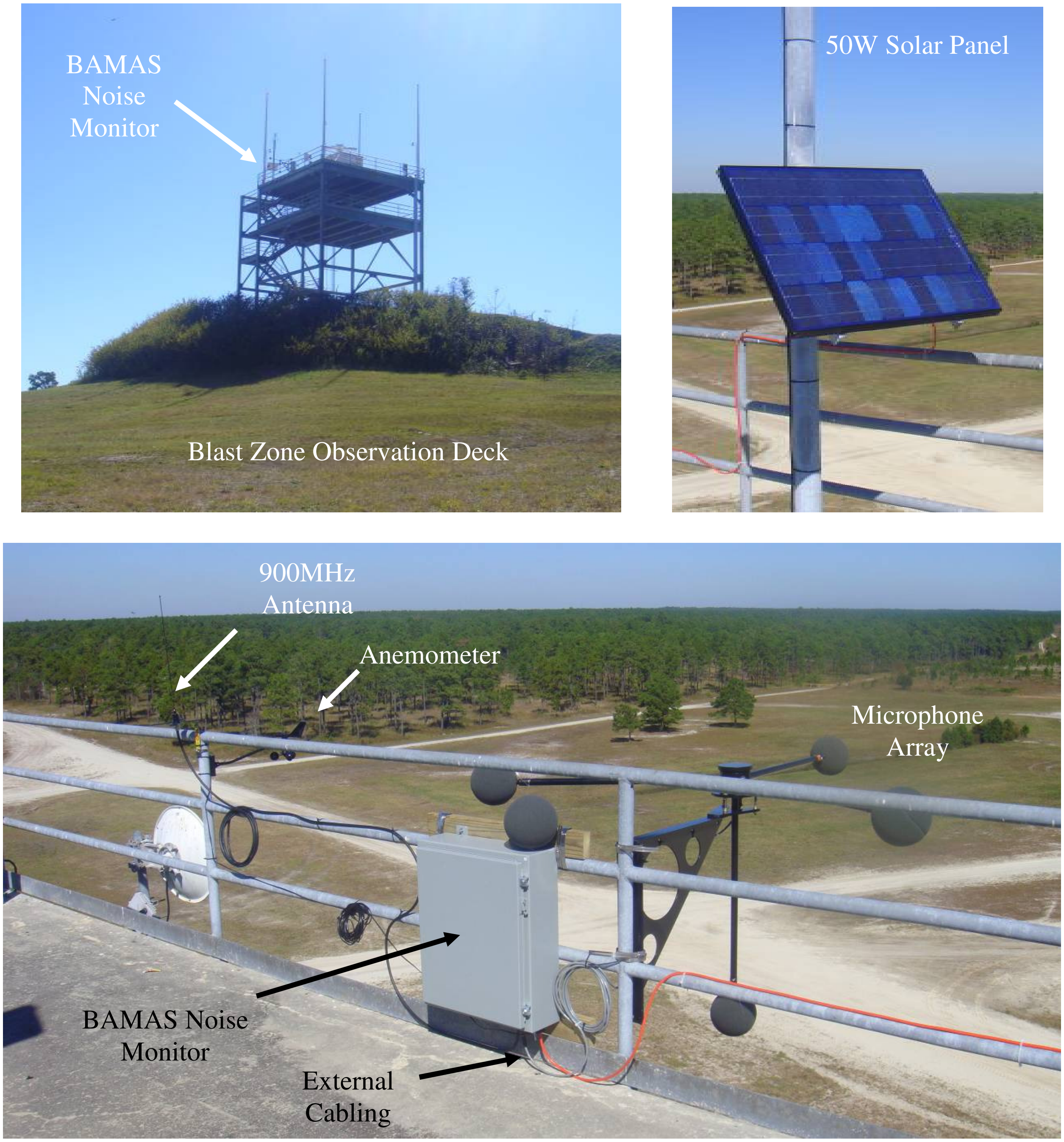


Figure 17: Node #2 Installation

After 2 months of continuous data collection, all of the data was downloaded for post analysis. Each archived detection has a individual file which includes the unprocessed microphone data, the BAMAS algorithm outputs, the classifier outputs, the current wind speed and direction, the battery voltage, and the system temperature. There were **3476** total blasts recorded by the BAMAS system during this 2 month collect. Node #2 archived the majority of blast (**2903**) because it is much closer to the blast zone than node #1 which archived only **249** blasts. All of the data presented in this report was taken from node #2 since there was not enough data at node #1 to measure performance accurately. Moreover, the blast data collected at node #1 was very low in SNR because the blast firing locations were very distant and an air conditioning unit located nearby generated high noise levels. Using an SPL meter, it was discovered that the air conditioning unit produced an ambient noise floor of 105 dB re. 20µPa.

Results

Figures 18-20 illustrate the different types of noise recorded by our system. Node #2 is located very close to a firing range, thus a lot of small arms fire (Figure 18) could be heard. The classifier is only designed to distinguish military impulse noise (explosions, impacts, and large caliber artillery fire) from wind noise (and other non-blast noise), thus only 142 (4.8%) of the total 2903 detections from node #2 were caused by small arms fire. We encourage the reader to reference the final report from SI-1585 for more information about the classifier performance.

The BAMAS noise monitors can detect levels much lower than existing systems because of the improved detection logic, increased A/D resolution, and lower noise floor. During our testing we set the system's input threshold at 95dB ref 20µPa peak. The event in Figure 18 had a peak level of 96 dB ref 20µPa.

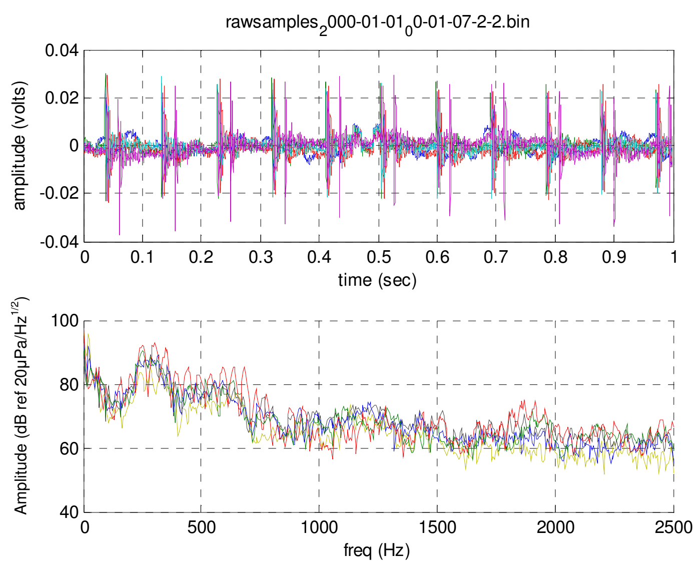


Figure 18: Small arms fire detected at node #2.

Figure 18 shows a typical blast event detected by our system. The software stores 1 second of raw data in order to fully capture the event (left). A zoomed-in version of the waveform on the left, shown on the right, reveals the different phase delays created by the microphone array. The BAMAS algorithm measures this delay in order to determine the DOA and to reject non-acoustic signals. The spectrum of this blast (Figure 20) shows that its fundamental frequency is 14.6 Hz with a peak level of 127 dB ref 20µPa.

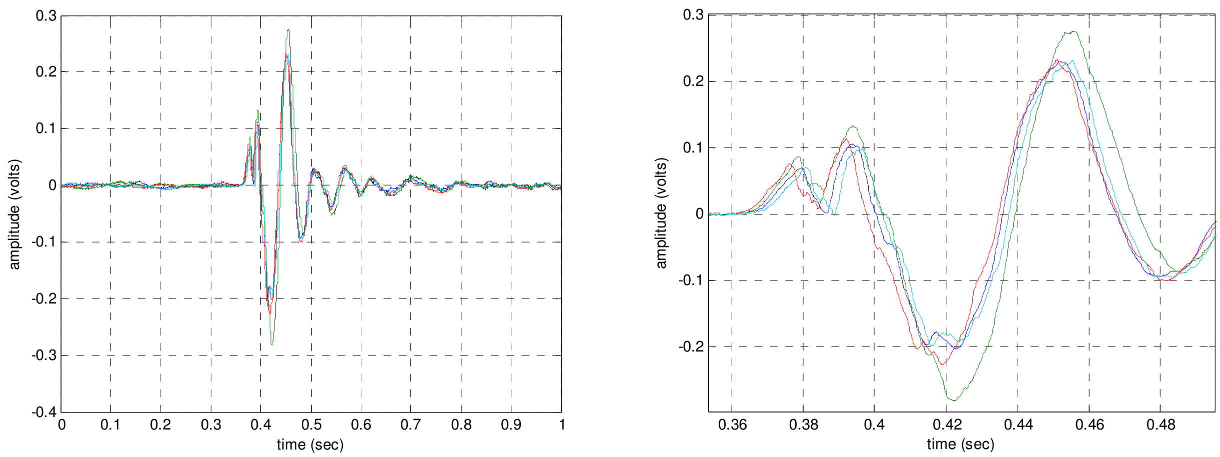


Figure 19: Blast noise detected by node #2. Each archived record writes 1 sec of data to disk (left). A close up (right) of the blast reveals the phase delay caused by the space-time filtering of the array. The BAMAS algorithm measures this phase delay to determine the DOA and to reject windborne noise.

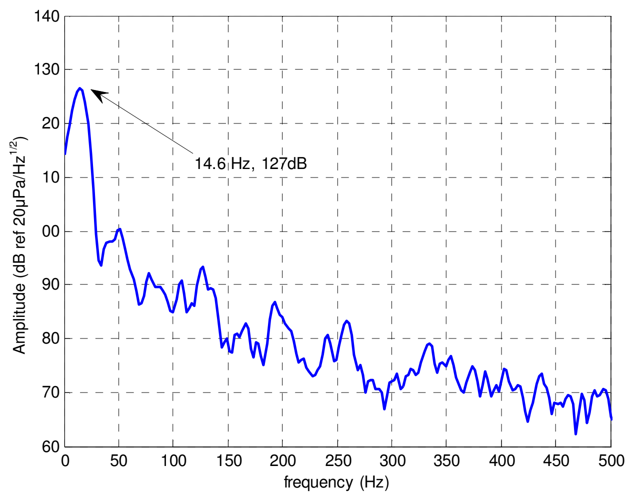


Figure 20: Frequency spectrum of blast noise (from Figure 19). The BAMAS algorithm samples each microphone channel at 5kHz. The signals of interest are generally low frequency such as this. This event was measured at 127dB ref 20µPa. The fundamental frequency is 14.6 Hz.

Over the course of 2 months the BAMAS system detected a large range of acoustic events: as low as 95 dB ref 20µPa (the threshold) and as high as 145 dB ref 20µPa (peak levels). A histogram and time series of the peak blast levels is shown in Figure 21. The peak levels reported in this figure were measured using a precision microphone which can vary slightly from the microphones in the array. A few detections beneath the 95 dB threshold in this figure indicate that there was some peak level mismatch between the array and precision microphones. The histogram of bearing indicates that there were locations at this base more active than others. The blast zone is a large area (2 square miles), so there is a large spread of activity between 80 and 110 degrees. The tall and skinny bars represent the direction to specific firing ranges – for example about 400 blasts were detected from due South (180 degrees).

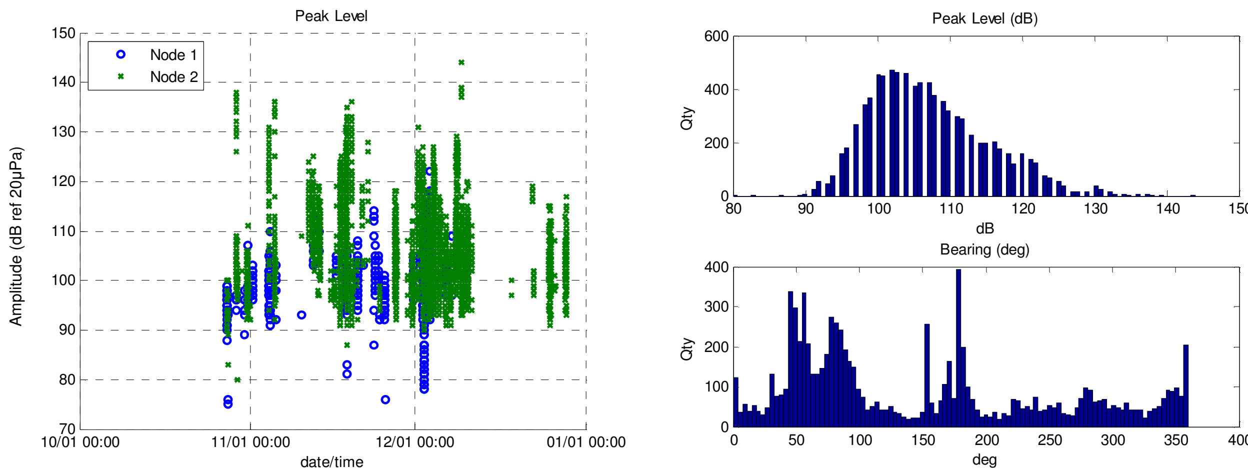


Figure 21: Peak level of blasts detected at Node 1 and 2 as a function of time (left) and plotted as a histogram (right). The peak level ranged from 95 - 145dB ref 20µPa with most occurring at 105dB ref 20µPa. Also shown is a histogram of the measured bearing which clearly shows that certain firing positions were being used more frequently than others. Node 2 was positioned at the center of the base which explains why it detected blasts from all directions.

After each detection, the BAMAS software passes the unprocessed microphone data (from only the precision ACO Pacific microphone) to the UPitt. classification code. This helps further mitigate any windborne impulsive noise that could possibly get through. Moreover, this code provides exceptional rejection of unwanted acoustic noise from aircraft and vehicles.

As a means to measure the wind rejection rate, the threshold in the acoustic likelihood was set artificially high. This allowed more non-blast noise to pass through to the classification algorithm and to be written to disk for post analysis. There were **5892** total detections reported by BAMAS algorithm. Of those, only **2903** were classified as blast noise by the U. Pittsburgh algorithm. To ensure the software classifier was working properly, each of these **2903** detections was replayed for a human observer to ensure that none were misclassified. Further analysis of the **2989** rejected events has not been conducted at this time but may be used to measure the number of false negatives.

The blue curve in Figure 22 illustrates the percentage of the detections as a function of their RMS time delay error. As described earlier, the RMS time delay error for blast noise should be very low. The curves in Figure 22 demonstrate that this is true for all of the data collected during the 2 month field test. **99%** of the blast noise detected by the BAMAS system (blue) has an RMS error less than our threshold (vertical dashed line). Moreover, all of the detections classified (by the U.Pittsburgh classifier) as “non-blast” have a very high error (the red curve). The large spike in the red curve was caused by a few detections that were incorrectly classified as “non-blast” when in fact they were actually “blast” noise. Close examination of the raw data that led to this inconsistency reveals that these signals were low magnitude (< 100 dB ref 20µPa) blast noise which is combined with some other type of noise source (both wind, aircraft, or vehicle). This corrupts the signal of interest and in most cases increases the RMS time delay error. In an attempt to isolate only wind events, we filtered through all of the detections and removed ones during when the wind speed was less than 4 mph. Of the total **5892** detections, there were **887** that recorded wind speeds in excess of 4 mph. As expected, the *pdf* remains largely unchanged except for the large spike which is now gone.

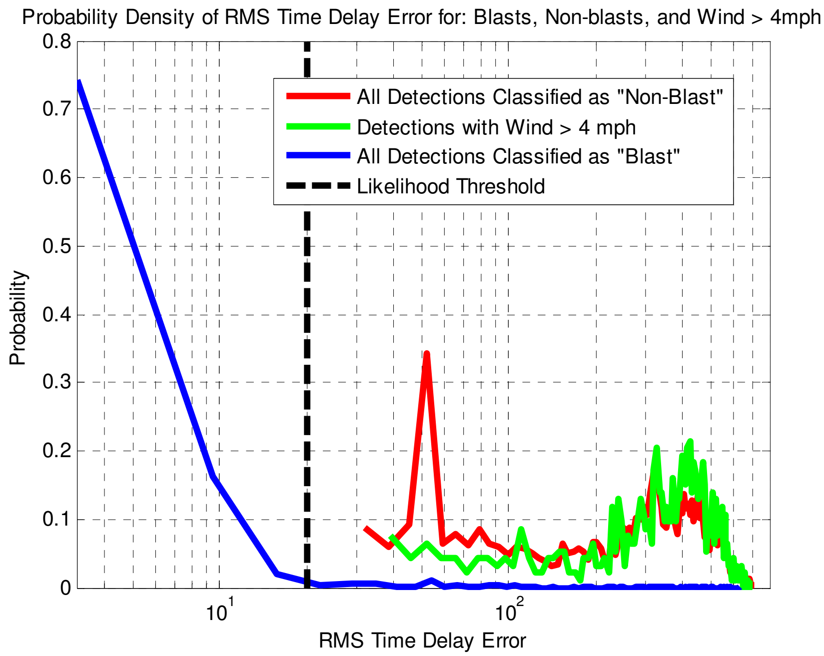


Figure 22: Probability density estimates for all detections classified as "Blast Noise" (blue), "Non-Blast Noise" (red), and all detections with wind exceeding 4 mph (green).

Further analysis of the **887** detections with wind in excess of 4 mph reveals that only **93** (**10%**) of them have an RMS error less than the optimal threshold (the vertical dashed line). These would normally be considered false detections since they pass our detection criteria, however, **38** (**4%**) of them were real blast noise, **52** (**6%**) were aircraft or vehicle noise, and only **3** (**< 1%**) were caused by wind. Based on these findings, we conclude that the probability of getting a false alert from wind noise is less than **1%** (a **99%** rejection rate). The rate of false alerts will vary at each location, but based on our measurements at node #2, this is about 1 per month. That being said, node #2 did not measure any significant wind events (Figure 30), in fact, nothing in excess of 15 mph was recorded.

Figure 22 also shows that there were a few impulse noise events (blue) that exceed the RMS error threshold – i.e. failed our test. These erroneously rejected events are referred to as miss detections (false negatives). The probability of miss-detecting a blast event can be measured by integrating (counting) their *pdf* above the chosen threshold. Of the **2903** impulse noise events measured, only **67** (**2.3%**) of them exceed the test threshold. This indicates that the probability of miss-detecting blast noise is **2.3%** and the probability of detecting blast noise is **97.7%**. The small percentage of miss detections is primarily caused by low SNR. Analysis of the **67** miss detections reveals that interference caused by excessive wind and nearby acoustic sources (aircraft and vehicles) corrupted these measured waveforms.

Figure 23 - Figure 27 illustrate different types of signals detected by the BAMAS system. Figure 23 is a large caliber artillery blast with 120dB ref 20μPa peak level and 15 Hz fundamental frequency. The cross-correlation (bottom) illustrates the measured phase delay between sensors. Note that all correlation peaks are close to 1 and fall within 5ms – the maximum possible acoustic propagation delay. This indicates that the waveforms measured at each microphone are nearly exact time delayed replicas. A comparison between this result and the cross-correlation of a wind event (Figure 27) indicates how spatial diversity can be used to reject wind events which are uncorrelated at large distances.

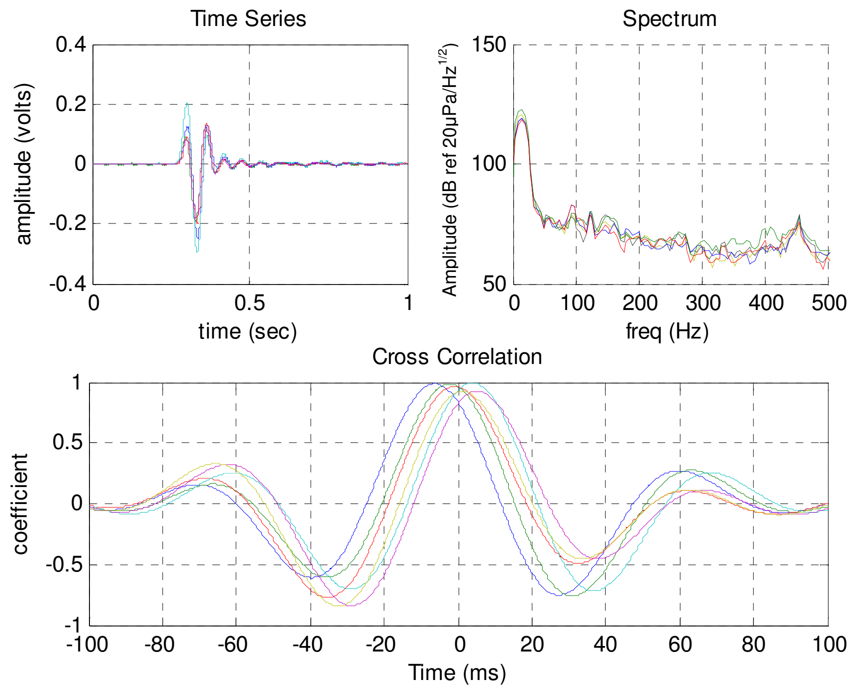


Figure 23: Example blast noise. This particular blast had a peak level of 120dB ref 20µPa. The cross-correlation (bottom) illustrates the measured phase delay between sensors. Note that all correlation peaks are about equal to 1 and fall within 5ms – the maximum possible acoustic propagation delay.

The military base where these BAMAS sensors are located has a very active airport. Many of the aircraft that land here support weapons training within the base, thus a combination of aircraft noise and large caliber artillery fire can be heard at the same time. Figure 24 illustrates data recorded by BAMAS node #1 of a single low-flying rotary wing aircraft passing overhead. The many harmonics shown in the are predominantly caused by aerodynamic noise (produced by the rotor). Moreover, the cross-correlations reveal a strong periodicity unlike impulse noise. This non-blast noise was registered as a false positive because the BAMAS algorithm is unable to discern between different sources of acoustic noise. The classification algorithm, however, does have this ability and therefore rejected this event.

Although infrequent, excessive wind and aircraft noise can corrupt the waveforms produced by impulse noise. Figure 25 and Figure 26 illustrate the waveforms measured when these events occur at the same time. In both cases, the impulse noise is the dominant noise source. As a result, the detection and classification algorithms produce the correct result. There is, however, a few cases where the opposite is true and this caused severe correlation loss (about 25% in the examples shown) and time delay mismatch. The RMS time delay error for these examples is higher than normal and in some cases will cause the event to fail our detection criteria. Based on the data collected during our 2 month field experiment, we determined that this will generally not happen unless the impulse noise SPL is less than 110 dB ref 20µPa. At levels greater than this, the impulse noise tends to dominant and therefore has sufficient SNR for classification.

During periods of excessive wind it was discovered that flow noise across the array structure generates vortex-induced vibration. This produces high frequency harmonics evident in the upper right plot of Figure 27. The acoustic flow noise is generally not well correlated between sensors, thus is ignored, and the induced vibration, which is well correlated between sensors, is not dominant. Moreover, waves produced by structural vibration propagate much faster than the speed of sound, so should be rejected in any case. In the event of both wind strumming and blast noise, the BAMAS algorithm will reject or detect based on the signal with the greatest power.

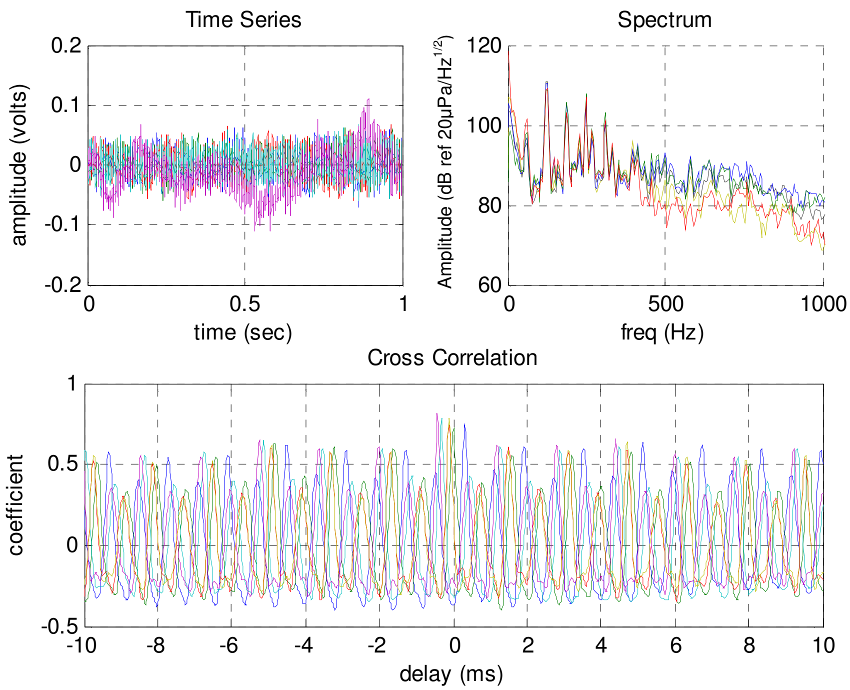


Figure 24: Example aircraft noise.

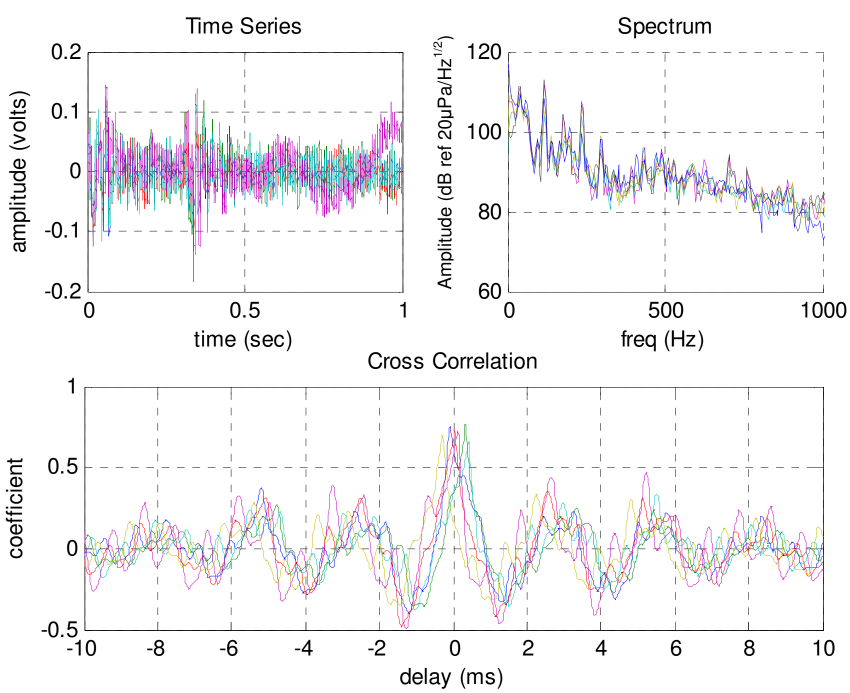


Figure 25: Example of aircraft and blast noise.

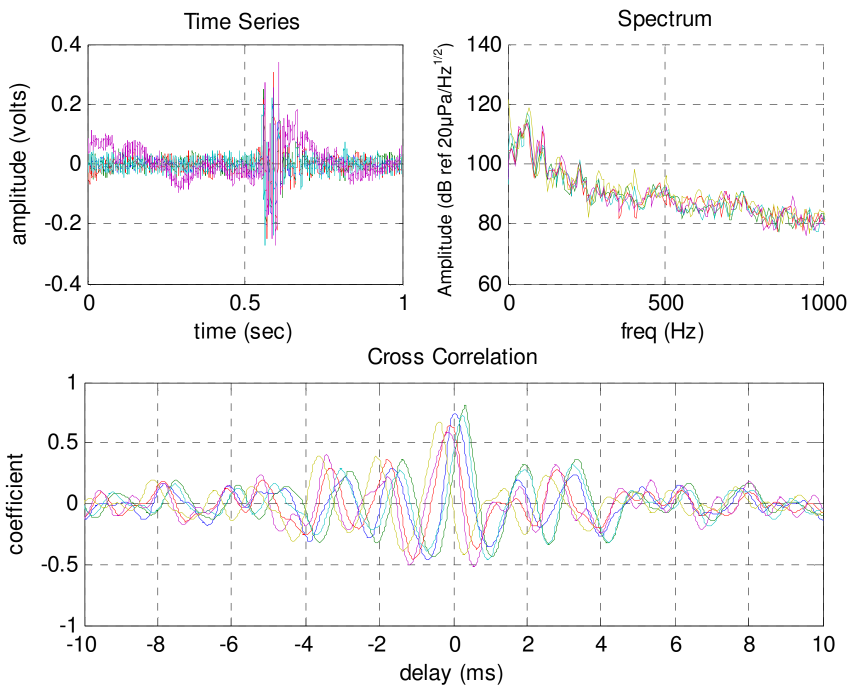


Figure 26: Example of wind and blast noise. Excessive wind noise can also corrupt blast signals. Note that the cross-correlation is much noisier than in Figure 23 and its peak is down 25%.

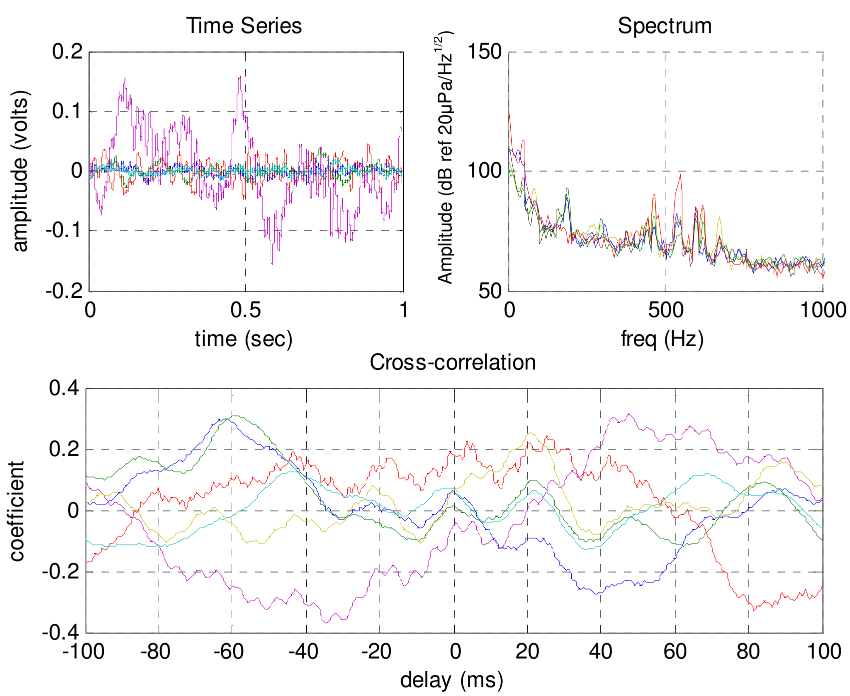


Figure 27: Example of vortex-induced vibration generated by wind flow over the array structure.

Figure 28 illustrates the output from the classification algorithm. To validate that detections were classified correctly, a human observer listened to all of the unprocessed data. It was determined that **2894** (**99%**) of those were blast noise, **12** (**<1%**) were vehicle noise, and **19** (**< 1%**) were a combination of aircraft, vehicle, and blast noise. This indicates that the observed probability of classifying a particular event as "blast noise" given actual blast events is **99%**. For more information regarding classifier performance, the reader is advised to reference the final report from SERDP project SI-1585, "Development and Implementation of Metrics for Identifying Military Impulse Noise".

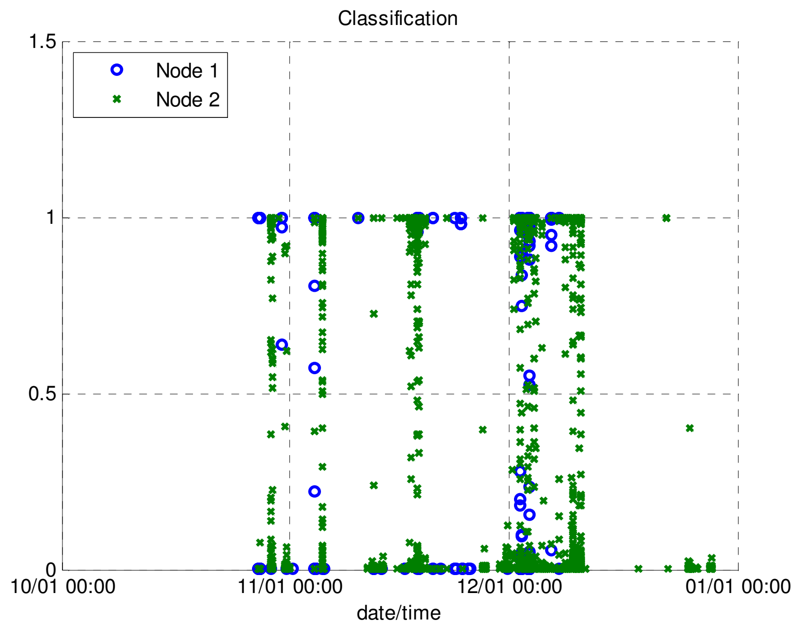


Figure 28: Time series of classifier output during the 3-month collect. Points above 0.5 are classified as "blast" and points beneath 0.5 are classified as "non-blast". This plot shows that there are a number of BAMAS detections that do not classify as blast noise. Most of these are caused by aircraft noise, vehicle noise, and other local acoustic noise sources. The BAMAS software does not display anything that classifies as a non-blast.

The design of the BAMAS software and electronics was driven by the necessity for a more reliable noise monitoring system. During our field testing, we discovered that the existing noise monitors, that we were attempting to get side-by-side comparisons with, were either not functioning properly or simply offline. Each BAMAS node is designed to telemeter health status information every 5 minutes. This includes information like battery, temperature, wind speed, and wind direction. This data can be exported from our base station (to Excel or Matlab) and is illustrated in Figure 29 - Figure 31. If the base station software detects that a node has gone offline (heartbeat timeout), it sends an email to bamas@gmail.com (this will be something different for each user) and attempts to restart it. During our field testing, the nodes went down only a few times when their batteries got low, but it would eventually recharge and com back online. A new version of the BAMAS design will include the option to be externally powered from an AC source. Both nodes were taken offline in December to facilitate a download of all of the raw data (used to produce this report).

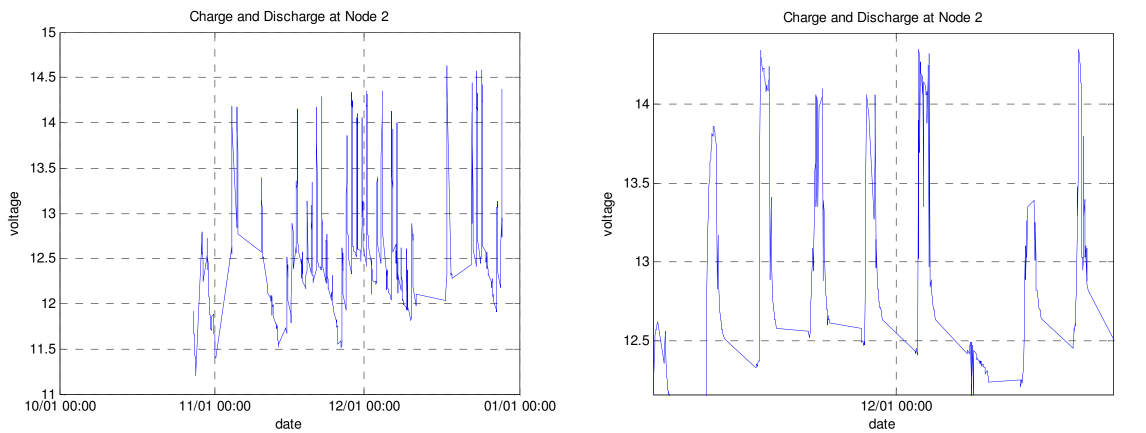


Figure 29: BAMAS noise monitor battery voltage reported by Node #2 over the course of 2 months (left) and 1 week (right). The 50W solar panel provides enough power to charge the battery quickly. The battery capacity will need to be increased to provide fulltime operation

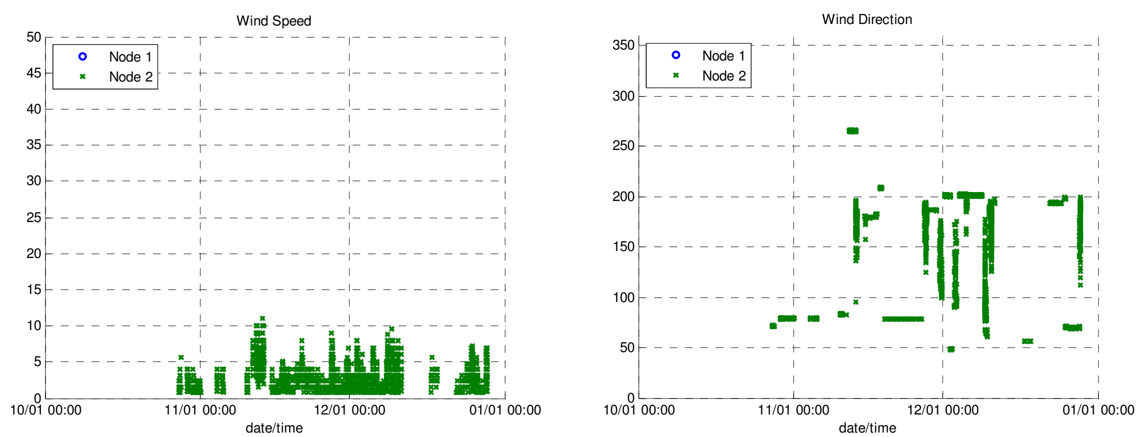


Figure 30: Average Wind speed (left) and wind direction (right) from Node #2 during the extended field testing.

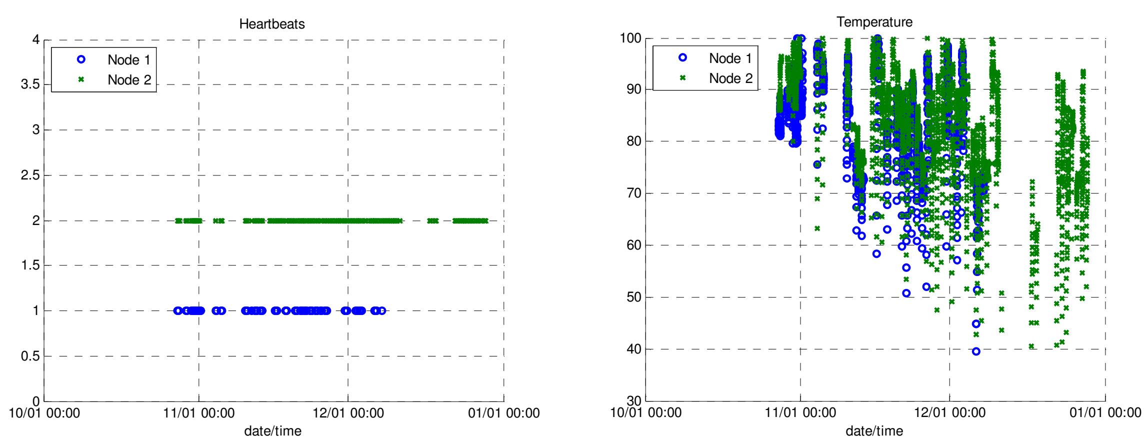


Figure 31: BAMAS sensor heartbeats (left) and temperature (right) during field testing.

During our week of on-site setup, installation, and testing, we noticed that low flying aircraft, particularly rotary-wing types, generated a lot of noise (between 90 and 110 dB ref 20µPa peak levels). Most of this aircraft noise was detected and archived by the BAMAS sensors. After a few days of data collection the U. Pittsburgh classifier was retrained with a new set of rotary wing data and the system no longer reports this type of noise. Figure 14 illustrates one complete day (November 4th, 2009) of detections reported by the BAMAS system. All of the noise during the morning period came from impacts in the blast zone (located at 50 degrees from Node #2). These blasts ranged anywhere from 100 to 130 dB ref 20µPa (peak level) and were all classified as "blast" noise. During the later half of the day, node #1 detected three individual moving targets. Each of these targets passed by node #1 in a south-to-north direction (as evident in the upper right plot in Figure 14). The raw data from these detections was downloaded and played back to confirm that each of the individual targets were rotary-wing aircraft. None of the detections produced by this target were classified as blast noise.

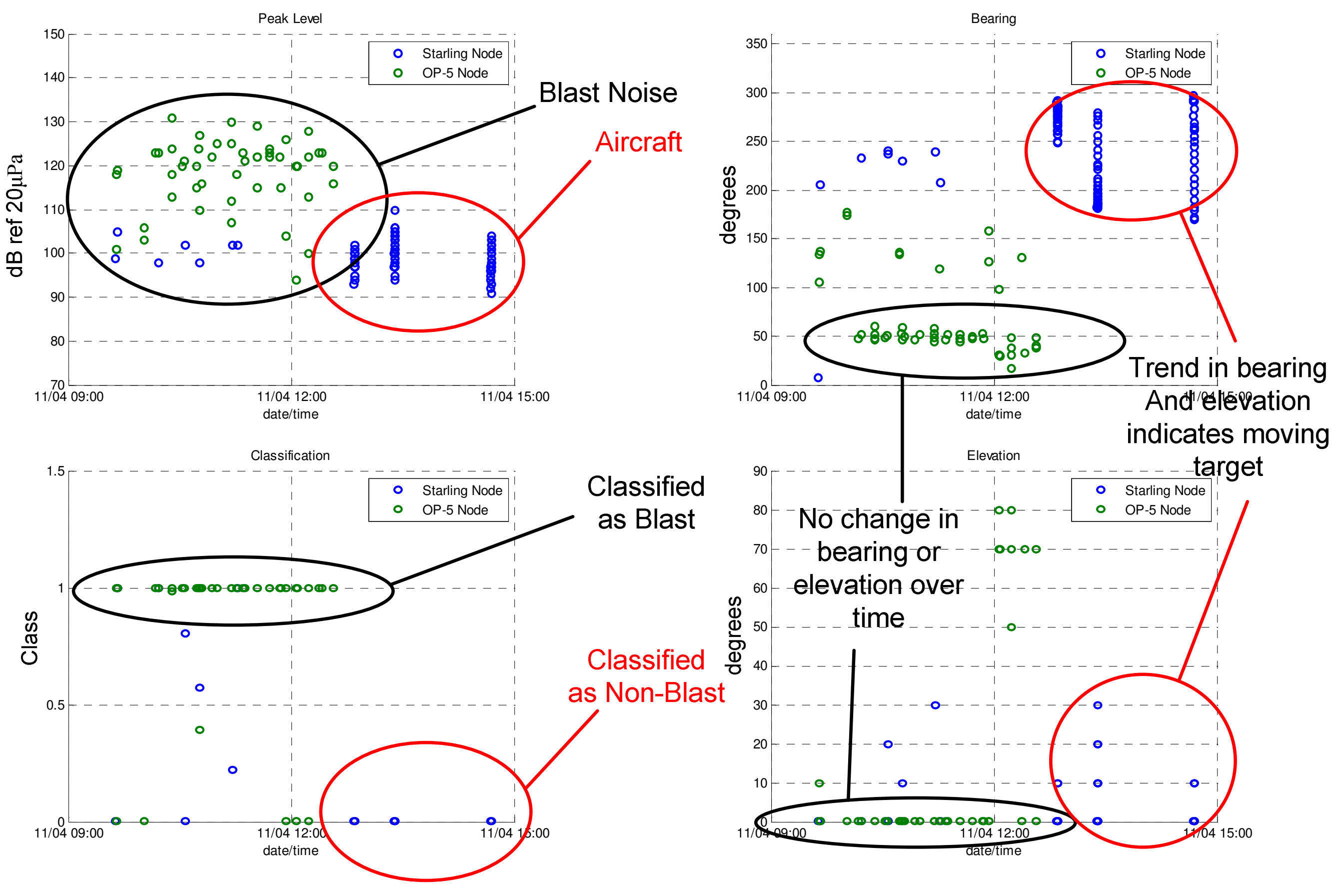


Figure 32: Demonstration of system's ability to discriminate between blast noise and aircraft noise.

Conclusions

This report summarizes an effort to develop an improved military impulse noise monitoring system with the combined technologies developed by Applied Physical Sciences Corp., under SI-1427, and the University of Pittsburgh, under SI-1585. Previous methodologies for rejection of windborne noise were unsuccessful and therefore a new method was devised under this effort using a 4 channel microphone array and associated detection and array processing. It was discovered that the cross-correlation metric can be made reliable so long as the time delays between sensors matches what is acoustically possible. This methodology has additional benefits including the ability to measure the bearing and elevation angle of the incoming blast. Moreover, in the case that two noise monitors detect the same blast noise, this information can be fused to estimate the latitude/longitude of the source.

The techniques introduced in this report have been tested and integrated into the APS BAMAS impulse noise monitoring system. The specific objectives of this new system are: (1) to detect, archive, and report all military impulse noise; (2) to reject false sources of non-military noise from wind and aircraft; (3) to measure direction-of-arrival (DOA) information and provide source triangulation; and (4) to develop improved software for user display and system maintenance. The classification algorithm discussed in this report was developed by the University of Pittsburgh who also co-sponsored the development of the BAMAS system. Two BAMAS sensors were built and installed at an active military base where they have been reporting blast noise for the past 2 months. Data presented in this report was extracted from unprocessed (raw microphone data) and processed (algorithm output) data recorded by the BAMAS sensors during this field testing. The BAMAS algorithm was found to reject 99.5% of the non-blast noise (specifically wind) recorded while retaining 97.7% of all blast noise. The system as a whole (sensors, base station, and software) functioned properly during field testing and is actively reporting new blast data to our online website/database. Users logged-in to our online tool may view blast noise in near real-time using an interactive spreadsheet and Google Earth mapping program.

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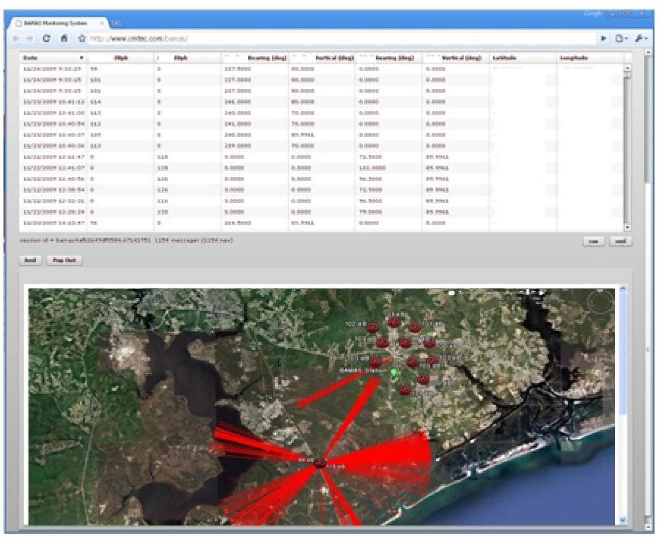
Appendices

Appendix I: System Datasheet

BAMAS Environmental Noise Monitoring System

Bearing and Amplitude Measurement and Analysis

- Advanced Environmental Noise Monitoring for Military Munitions and Aircraft Noise
- Real-time Signal Processing for Event Detection and Classification
- Noise Source Localization
- Works in Windy Conditions Without Generating False Events
- Automated Recording and Email Notifications
- Secure Web Tool for Data Analysis and Visualization



The BAMAS system is a collection of remote sensors designed for detection, localization, and classification of environmental noise sources from military and aircraft noise. Military noise is characterized by loud, low frequency, short-duration acoustic pulses from explosions, impacts, and large caliber artillery fire. BAMAS sensors automatically detect and report these events using a calibrated acoustic array capable of resolving the direction of an incoming pressure wave. This array also provides the ability to mitigate false positive events created by windborne noise. Other noise monitoring systems do not have this technology and therefore report many false events during inclement weather thus skewing detection statistics and post analysis. Additionally, the BAMAS real-time processor employs special detection and classification algorithms developed by APS and researchers at the University of Pittsburgh to provide a statistical measure of the likelihood of each detected event to further rule out unwanted false positives.

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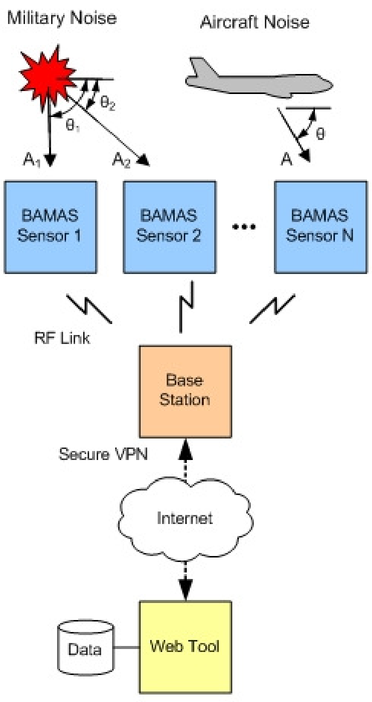
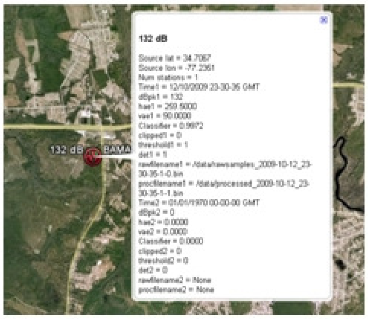
BAMAS Environmental Noise Monitoring System

Each BAMAS sensor includes a 4 channel microphone array, solar panel, weather station, RF antenna, electronics panel, cabling, and mounting hardware. The system is intended for long term and permanent surveillance applications in remote locations without the necessity for AC power.

BAMAS sensors employ a low power PC/104 based processor and data acquisition modules running embedded Linux and real-time array processing code. Detected events are recorded locally and information regarding its bearing and amplitude are telemetered to a base station computer via a long distance Ethernet radio. This data is fused at the base station with information from other BAMAS sensors and is sent to our web-based tool via email.



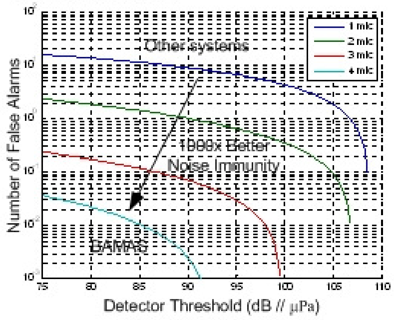
The online tool includes a database of events and a Google Earth map for visualizing their location.



Unlike other noise monitoring systems, BAMAS triangulates the location of offending noise sources and drops a waypoint at that location on the Goggle Earth map. Peak level, time, location, classified output, directional-of-arrival (DOA), file name and other information is easily viewed by clicking on individual waypoints.

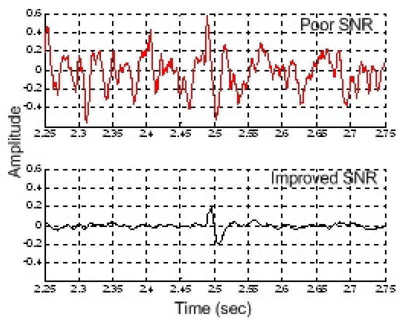
The BAMAS software has been designed to minimize operator labor. Automated emails notify the user when the batteries get low, if a sensor goes offline, or when a certain number of events of exceedingly high amplitude are detected. Moreover, downloading event time series data is facilitated over the Ethernet connection and can be scheduled to download automatically during periods of little activity. Data presented on the secure BAMAS website is easily converted and viewed in other spreadsheet and analysis software programs. Currently, data may be converted to CSV, XML, or KML files. Most internet browsers may be configured to automatically load and display this data.

BAMAS sensors run real-time signal processing codes to estimate the noise source location and to reduce the possibility of false events. To reduce false positives as a result of windborne noise, the software measures the propagation speed of each pressure signal and rejects all that do not travel at the speed of sound – hence all non-acoustic events are discarded. Other noise monitoring systems use a single microphone and are therefore highly susceptible to reporting false detections. Windborne events can bias noise statistics to the point where meaningful assessment of acoustic sound power levels is not possible or requires and unreasonable amount of manual analysis. The figure below illustrates the performance of the BAMAS system versus all other monitoring systems employing a single microphone.



The four curves represent the false alarm rate as a function of detection threshold using 1, 2, 3, and 4 microphones. The BAMAS array uses 4 microphones, so the possibility of a detecting a false event is 1000 times less likely than it is for a single channel system. This means that the BAMAS system will report 1 false alarm for every 1000 reported by other systems.

Further mitigation of windborne events is accomplished using cross-channel correlation analysis, beamforming, and classification. The figure below illustrates the SNR improvement after beamforming. Wind noise in the upper plot conceals an impulsive noise event that can only be discerned in the lower plot – after beamforming. In addition to improving the signal quality, this prevents the possibility of missing real events. A neural-net classifier is used after to assess the likelihood of an acoustic impulse event and may be extended for other sources.



Applied Physical Sciences

BAMAS Environmental Noise Monitoring System

Applications

- Military, industrial and community noise monitoring
- Aircraft noise monitoring
- Acoustic modeling and propagation studies
- Persistent surveillance during inclement weather
- Noise localization
- Noise classification (blast, aircraft, wind, etc.)

Acoustic Specifications

Measurable Sound Pressure Level	80-145 dB re. 20μPa
Effective Noise Floor	75 dB re. 20μPa
Acoustic Frequency Response	0.5 Hz – 20 kHz
Bearing Resolution Bearing Accuracy	0.5° 1°
Vertical Angle Resolution Vertical Accuracy	10° 15°
Sample Rate	4 kHz (Adjustable to 20kHz)
Data Processing Window	1 second (Adjustable)
Data Processing Window	1 second (Adjustable for longer signals)

Environmental Specifications

Temperature	-20 – 60 °C

Electrical Specifications

Battery	12V lead acid
Communications	900MHz Ethernet (Unlicensed)
Remote ON/OFF Control	9600 baud Serial Port

Software

BAMAS Sensor	Embedded Linux
BAMAS Base Station	Windows/Linux
BAMAS Website	IE / Chrome

Ordering Information

Jeffrey Allanach
jallanach@aphysci.com
(860) 448-3253 x 105

Development of this system was supported by the US Department of Defense through the Strategic Environmental Research and Development Program (SERDP) under the task area of Sustainable Infrastructure (SI-1427).

System Components

Appendix II: Derivation of Acoustic Likelihood Test Threshold

The acoustic likelihood test derived here is intended to decide if measured channel-to-channel time delays, from the output of a cross correlation, originate from acoustic sources or spurious false alarms caused by elevated levels of wind noise. These signals may be represented by the hypotheses,

$$\begin{aligned} H_0 &: \tau_i \sim \mathrm{N}\left(\tau_i^a, \sigma_\tau^2\right) \\ H_1 &: \tau_i \sim \mathrm{U}(-\tau_{\max}, \tau_{\max}) \end{aligned},$$

where in the case of an acoustic signal, H_0, the channel-to-channel time delays (τ_i) derived from $R_{xx}(\tau)$ are normally distributed around the actual channel-to-channel time delays (τ_i^a) with variance inversely related to the signal bandwidth. In the case of a spurious false event, the time delays can be assumed uniform within the interval $[-\tau_{\max}, \tau_{\max}]$. According to the Neyman-Pearson Lemma, the optimal decision, in the sense of minimizing the probability of a missed detection, subject to a constant false alarm rate is based on the likelihood ratio,

$$\Lambda(H_0, H_1) = \prod_i \frac{p(\tau_i \mid H_1)}{p(\tau_i \mid H_0)} \underset{"H_0"}{\overset{"H_1"}{\gtrless}} \Lambda_0,$$

where we decide "H_0" or "H_1" in the event that the ratio is less than or greater than the threshold. Based on the hypotheses defined above we can solve for the threshold as,

$$\Lambda(H_0, H_1) = \frac{\prod_i p(\tau_i \mid H_1)}{\prod_i p(\tau_i \mid H_0)} = \frac{\prod_i \frac{1}{\sqrt{2\pi\sigma_\tau^2}} \exp\left(\frac{-\left(\tau_i - \tau_i^a\right)^2}{2\sigma_\tau^2}\right)}{\prod_i \frac{1}{2\tau_{\max}}} = \frac{1}{c} \prod_i \frac{1}{\sqrt{2\pi\sigma_\tau^2}} \exp\left(\frac{-\left(\tau_i - \tau_i^a\right)^2}{2\sigma_\tau^2}\right).$$

$$= \frac{1}{c} \prod_i \exp\left(\frac{-\left(\tau_i - \tau_i^a\right)^2}{2\sigma_\tau^2}\right) = \frac{1}{c} \exp\left(\sum_i \frac{-\left(\tau_i - \tau_i^a\right)^2}{2\sigma_\tau^2}\right) = \frac{1}{c} \exp\left(\sum_i \left(\tau_i - \tau_i^a\right)^2\right)$$

Here we use the constant c to absorb a number of constants. Our test then reduces to,

$$\varepsilon = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\tau_i - \tau_i^a\right)^2} \underset{"H_0"}{\overset{"H_1"}{\gtrless}} \Lambda_0,$$

which is known as the root-mean square error (RMSE). Since we assumed (under H_0) that the time delays are normally distributed, the following relationship holds

$$\tau_i = \tau_i^a + w_i$$

where w_i is zero-mean Gaussian noise. This implies that we can quantify the RMSE in terms of w_i as,

$$N\varepsilon^2 = \sum_i \left(\tau_i - \tau_i^a\right)^2 = \sum_i w_i^2 = q \sim \chi_N^2 \,,$$

where the random variable q is equal to a sum of N squared independent Gaussian random variables w_i. $q \sim \chi_N^2$ is known as a chi-squared distribution with N degrees of freedom. The chi-squared distribution is used often in confidence tests of state estimators and is being used here in a similar manner to measure the "chi-squared goodness-of-fit". This can be interpreted as a measure of how well the data fits, or approximates, a series of independent zero-mean normally distributed random variables. For our purposes the goodness-of-fit test will be used to find the 99% confidence region defined as,

$$P\left\{\frac{N\varepsilon^2}{\sigma_\tau^2} > b\right\} = \frac{\delta}{2} \,,$$

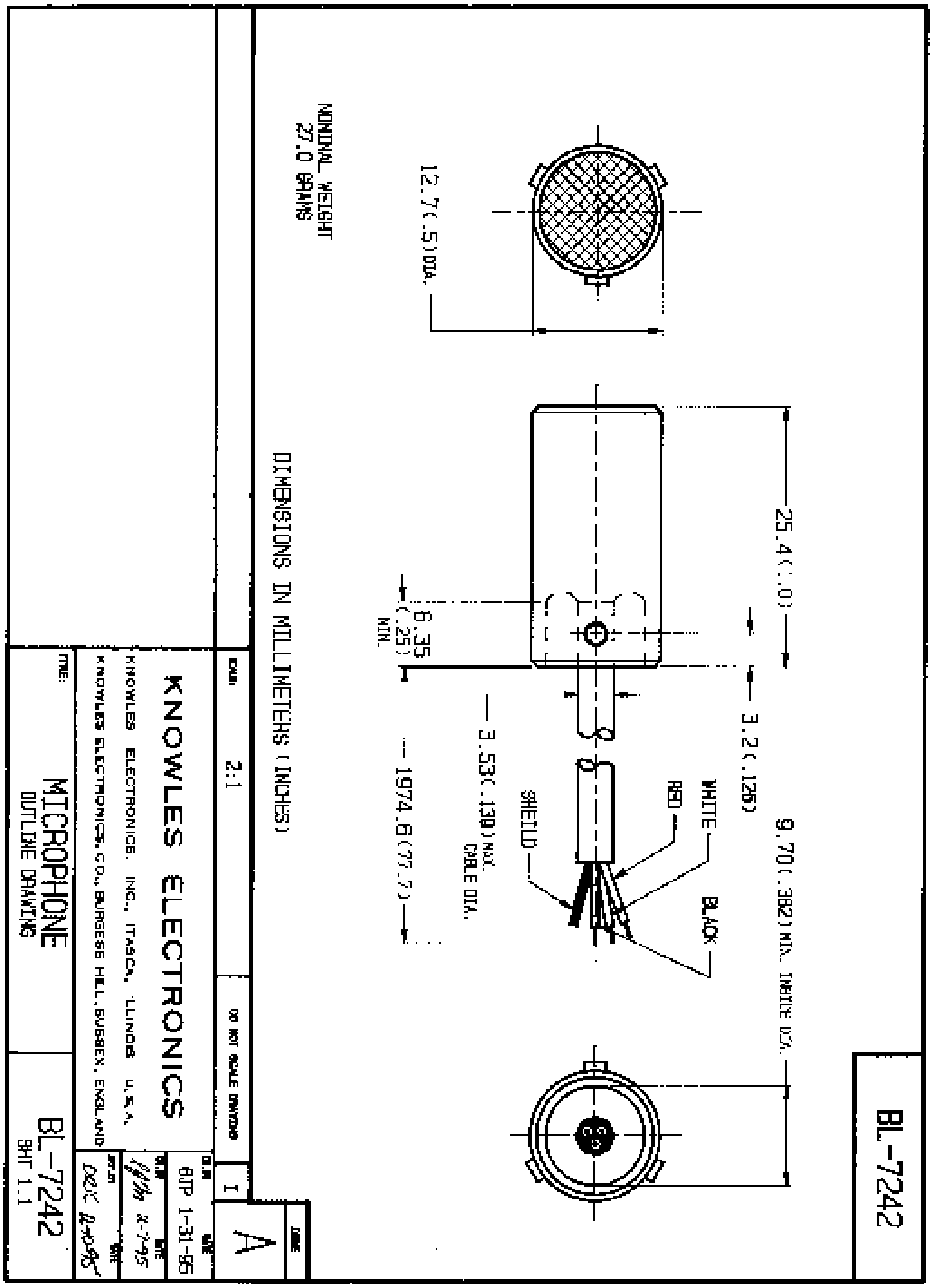
where we have omitted the lower threshold since we are not worried if the measured time delays exactly match the expected time delays, this is theoretically impossible, but practically feasible since the performance of our signal processing is limited in resolution and prone to quantization error. The threshold (b) that yields our 99% confidence region is given by,

$$b = \chi_N^2 \left(1 - \delta/2\right) = \chi_N^2 \left(99\%\right) = 16.81 \,,$$

and then our new test statistic is,

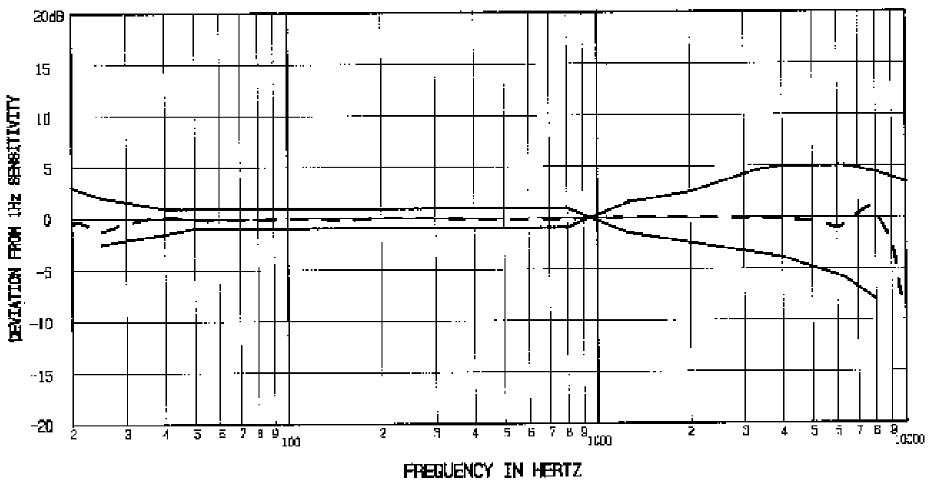
$$\frac{N\varepsilon^2}{\sigma_\tau^2} < 16.81 \,.$$

Appendix III: Knowles BL-7242 Microphone Data Sheet



BL-7242
SHT 2.1

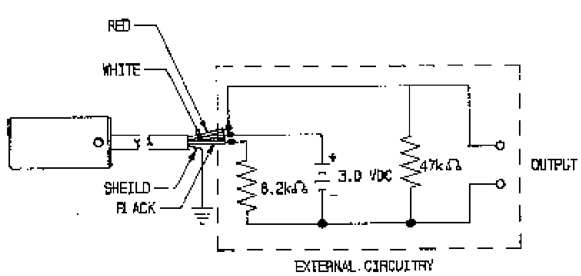
NOTE:
When test limits are used to establish incoming inspection acceptance/rejection criteria, correlation of test equipment with Knowles is also required for elimination of equipment and test method variations.



1. ALL CHARACTERISTICS ARE UNDER THE TEST CONDITIONS SHOWN IN #9 BELOW.
2. PRESSURE SENSITIVITY IN dB RELATIVE TO 1.0 VOLT/MICROBAR (0.1 N/m)
3. DC SUPPLY: 3.0V
4. BATTERY CURRENT DRAIN: 150uA MAX.
5. OUTPUT IMPEDANCE: 4000 OHMS NOMINAL.
6. OUTER HOUSING TO SHIELD: 3.0 OHMS MAX.
7. "A" WEIGHTED NOISE (1kHz EQUIVALENT SPL): 34 dB MAX.
8.

	SENSITIVITY			DEVICE CONFORMITY	
FREQUENCY	MIN.	NOM.	MAX.	RANGE OF DEVIATION FROM 1 kHz	
20	—	—	—	—	+3.0
25	—	—	—	-2.5	+2.0
31.5	—	—	—	-2.0	+1.5
40	—	—	—	-1.5	+1.0
50	—	—	—	-1.0	+1.0
800	—	—	—	-1.0	+1.0
1000	-72.0	-69.0	-66.0	0.0	0.0
1250	—	—	—	-1.5	+1.5
1600	—	—	—	-2.0	+2.0
2000	—	—	—	-2.5	+2.5
2500	—	—	—	-3.0	+3.5
3150	—	—	—	-3.5	+4.5
4000	—	—	—	-4.0	+5.0
5000	—	—	—	-5.0	+5.0
6300	—	—	—	-6.0	+5.0
8000	—	—	—	-7.5	+4.5
10000	—	—	—	—	+3.5

9. TEST CONDITIONS:



TITLE: MICROPHONE PERFORMANCE SPECIFICATION

KNOWLES ELECTRONICS
KNOWLES ELECTRONICS, INC., ITASCA, ILLINOIS U.S.A.
KNOWLES ELECTRONICS CO., BURGESS HILL, SUSSEX, ENGLAND

BL-7242 SHT 2.1

DR. BY GJP DATE 1-31-95
CK. BY DATE 2-7-95
APP. BY DATE 2-10-95

ISSUE A

Appendix IV: ACO Pacific 7052LF/4052LF

Note: The preamplifier on this microphone was modified so that the usable frequency range was expanded from 20Hz – 20kHz (indicated below) to 0.5Hz – 20 kHz.

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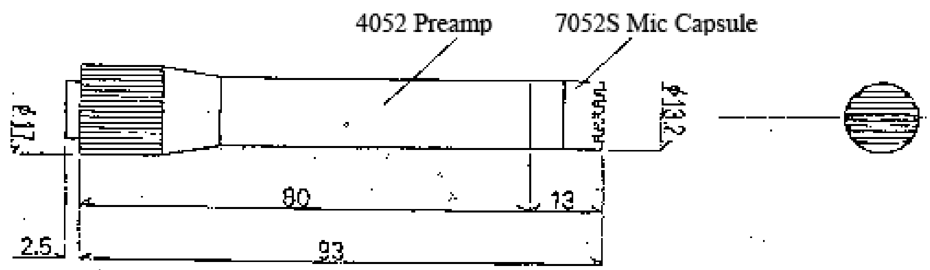
7052S/4052
OEM TYPE 1.5
MEASUREMENT
MIC/PREAMP

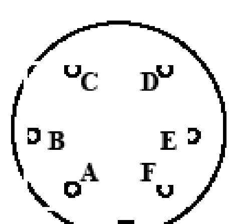


The **7052S/4052** Measurement Microphone/Preamp is intended for OEM applications requiring a **cost-effective,** stable, flat, and rugged mic. The back electret construction eliminates the need for any polarizing voltage. The **Titanium diaphragm** assures both short and longterm stable frequency and amplitude response over a wide range of environmental conditions. The performance **exceeds IEC** specifications for **TYPE 2** microphones. It does not meet TYPE 1 specifications - Thus the reference to TYPE 1.5 performance. Options Starburst Grid (GRD2), LF Response Testing, 4052 LF response extension

SPECIFICATIONS

Frequency Response: **20 Hz to 20 kHz** +/- 3dB Determined by the preamp
Sensitivity: 7052S Capsule - (-)**33dBV/Pa** (20 mV) Open Circuit
Preamp Loss: -**2 dB Typ**
Preamp Operating Voltage: **(+)9Vdc to 15 Vdc**
Usable Dynamic Range: **24 dBA** (equivalent "A" weighted noise floor)
Upper Limit (Determined by Preamp Operating Voltage)
9Vdc - **130 dBSPL**
15 Vdc - **140 dBSPL**
Preamp Connector - Cable - ACO Pacific Model Number **7052SC**
Connector Pinout:
Pin A - **(V+)** Pin B - **N/C**
Pin C - **Signal** Pin D - **N/C**
Pin E,F -**(V-)** Shield at Equipment End

Rev. A 6/95 - Connect Pin B to E&F -Not necessary after1/98



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